TECHNOLOGY DEPARTMENT

THE JOURNAL OF THE INSTITUTION OF PRODUCTION ENGINEERS

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GOBLIN AND GHOST JET PROPULSION ENGINES
by J. L. EDWARDS.

PROBLEMS RELATING TO THE PRODUCTION OF EXPERIMENTAL GAS TURBINE COMPONENTS
by R. MILLER.

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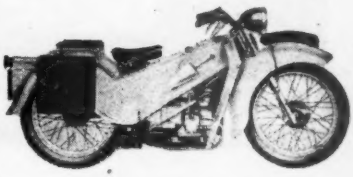

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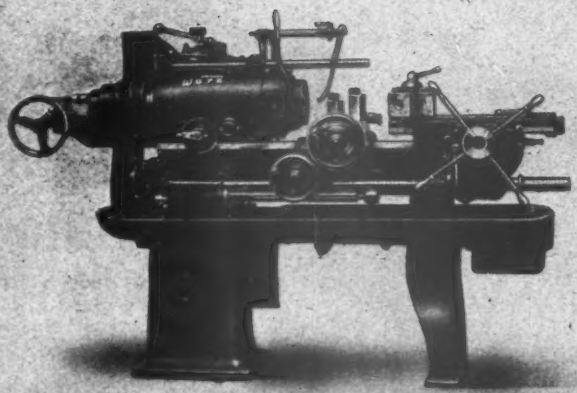

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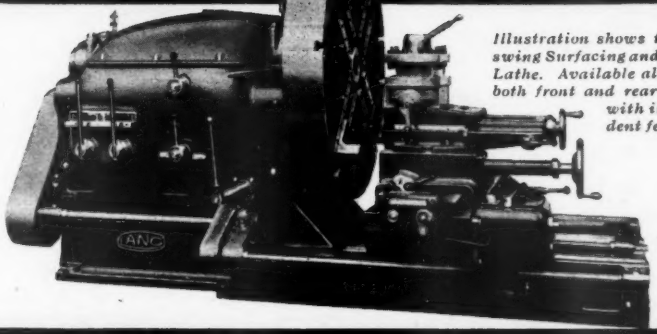

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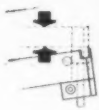

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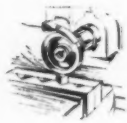

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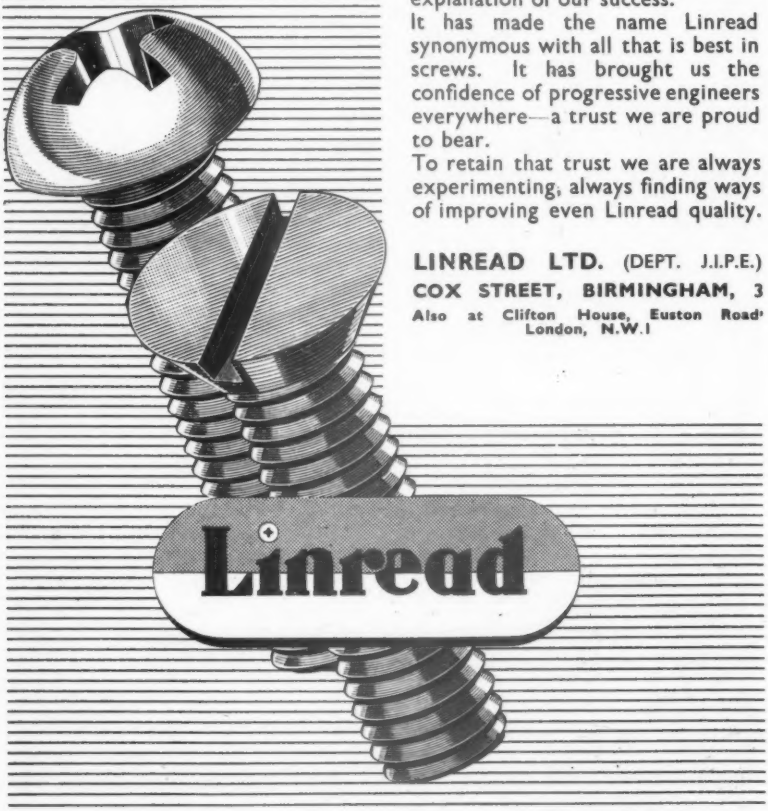

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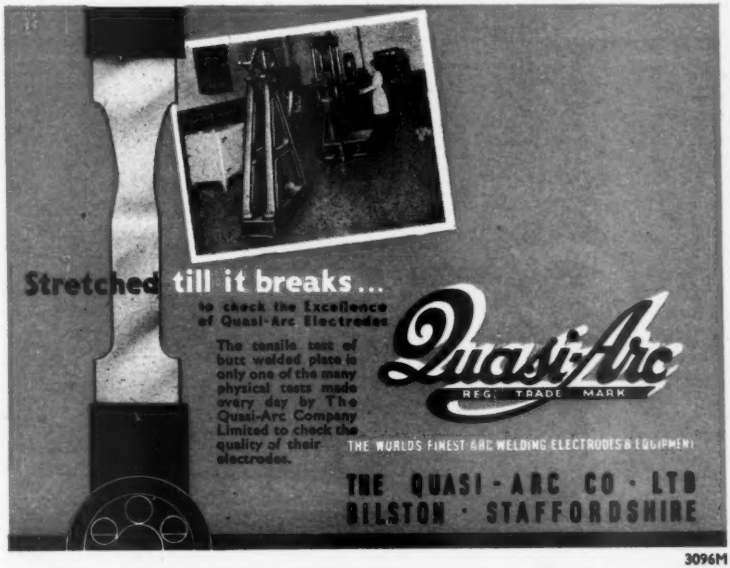
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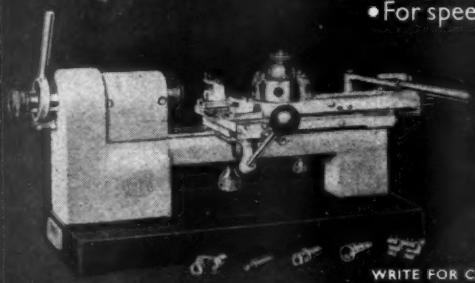

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INSTITUTION NOTES

April, 1949

MEETING OF COUNCIL The next meeting of Council will be held on Thursday, 28th April, 1949, at 36, Portman Square, W.1, at 11-00 a.m., and will be followed by an Extraordinary General Meeting at 4-00 p.m.

MEASUREMENT OF PRODUCTIVITY The Joint Committee of the Institution of Production Engineers and the Institute of Cost and Works Accountants, which is investigating means of measuring productivity and devising methods of applying this measure for increasing production, has met four times since the One-day Conference held in London in November.

Well-known manufacturing organisations in London are co-operating in the work of the Committee, and Trade and Technical Associations are showing a keen interest in the subject.

GUSTAVE-L. GERARD PRIZE The Comité National Belge de l'Organisation Scientifique announces the forthcoming award of the Gustave-L. Gerard Prize, for the best original and unpublished article on an industrial management subject.

The prize, which is the sum of 25,000 francs (Belgian), is being awarded to mark the retirement of the President of the C.N.B.O.S., M. Gustave-L. Gerard. Full particulars may be obtained from the Secretary of the Overseas Relations Co-ordinating Committee, British Institute of Management, 17 Hill Street, London, W.1.

SHEET & STRIP METAL USERS' TECHNICAL ASSOCIATION The Council of this Association extends a warm invitation to members of the Institution to attend the Spring Meeting to be held in the Grosvenor Suite, Grand Hotel, Birmingham, on Wednesday, April 13th, 1949, at 6-30 p.m.

Dr. H. A. Dickie, of the Research Department of Stewarts and Lloyds, Ltd., will give a paper on "Improving Bessemer Steel Quality for the User," which will deal with important new developments in steel production.

It is hoped to provide preprints of the paper, which may be obtained from the Hon. Secretary, Sheet and Strip Metal Users' Technical Association, 49 Wellington Street, Strand, W.C.2.

TECHNICAL COLLEGE, BRADFORD Applications are invited for appointment as Senior Assistant in the College with suitable qualifications in Economics, Industrial Administration and Man-

agement. The Senior Assistant will also act as Assistant to the Principal. The salary, including allowances, will be in accordance with the Burnham Scale. Further particulars may be obtained from the Director of Education, Town Hall, Bradford.

BRITISH STANDARDS INSTITUTION The following Standards have recently been issued and are obtainable from the British Standards Institution, 28 Victoria Street, Westminster, S.W.1., price 2s. each, post free :

Standards Issued	*I.P.E. Representative on the Appropriate B.S.I. Committee*
387 : 1948—The attachment and drive of circular metal cutting saws for cold working.	Mr. H. Nutton, M.I.P.E.
1478 : 1948—Bending dimensions of bars for concrete reinforcement.	Mr. H. W. Hobbs, M.I.P.E.
1498 : 1948—Gear Hobbing Machines for Turbine and similar drives.	Mr. A. Sykes, M.I.P.E.

The undermentioned draft B.S. Specification is now available for comment :

CK(WEE)656—Draft British Standard for Steel Filler Rods for Gas Welding of Mild Steel.
Latest date for receipt of comments ... 26.4.49

This draft has been prepared by B.S.I. Committee WEE/20 on which the Institution is represented by Mr. E. E. Alflatt, A.M.I.P.E. Copies can be obtained gratis from the British Standards Institution provided that mention is made in the letter of application that the writer is a member of the Institution of Production Engineers.

NEWS OF MEMBERS

Mr. Andrew Blyth, A.M.I.P.E., has been appointed General Manager of William Mills, Ltd., of Wednesbury, Staffs.

Mr. H. C. Cleaver, Grad.I.P.E., has been appointed Lecturer in the Department of Engineering, at the Cape Technical College, Capetown.

Mr. N. H. Dixon, Grad.I.P.E., has been appointed Assistant General Manager to Charles S. Green & Co. Ltd., Birmingham.

Mr. A. Tildsley, Junior, Int.A.M.I.P.E., is now General Manager of the Reliance Gear Company.

Mr. W. H. Hedger, Int.A.M.I.P.E., A.M.I.Mech.E., has been appointed leader of the rocket group of the Armaments Division of Armstrong Whitworth Aircraft Co. Ltd., Coventry.

Mr. C. Hodson, Int.A.M.I.P.E., is now District Manager of Alfred Herbert Ltd., Coventry.

Mr. T. Knowles, A.M.I.P.E., was recently appointed Managing Director of Barfield Engineering Co. Ltd., New Milton, Hampshire.

Mr. A. F. Law, A.M.I.P.E., has been appointed Chief Engineer of Mettoys, Ltd., Northampton.

Mr. O. E. Trivett, Int.A.M.I.P.E., has now taken up the position of Chief Engineer of Radio & Electrical Manufacturing Co. Ltd., Bangalore City, S. India.

VISITOR FROM ABROAD Mr. Richard B. Spiro, M.I.P.E., Export Manager of The Coleman Lamp and Stove Co. Ltd., of Toronto, Canada, is due in England this month for a brief visit. Mr. Spiro is a member of the South African Branch of the Institution, but for the last 15 years has been closely connected with American and Canadian industry.

OBITUARY The Institution has learned with deep regret of the death of Mr. Philip Bevan, M.I.P.E., of Sydney Section, Managing Director of Associated Machine Tools (Australia) Pty. Ltd., and Director of McPherson's Ltd.

He was associated with the machine tool trade in Australia for many years, and through his foresight the machine tool manufacturing facilities of the country were increased when he merged the interest of his company—E. P. Bevan & Sons—with that of McPhersons Ltd., and formed the Associated Machine Tools (Australia) Pty. Ltd.

Mr. Bevan was one of the first members of the Institution in Australia, and it was largely through his enthusiastic assistance and encouragement that the Sydney Section was inaugurated. His passing will be sincerely mourned by his many friends and colleagues.

The Institution also announces with great regret the deaths of Mr. F. P. Donovan, M.B.E., A.M.I.P.E., of London Section ; Mr. J. Eccles, A.M.I.P.E., of Preston Section ; and Mr. A. E. Parker, Stud.I.P.E., of London Graduate Section.

BOOKS RECEIVED *Diamond Tool Patents III—Truing of Grinding Wheels*, by W. Jacobsohn, A.M.I.Mech.E. (Industrial Diamond Information Bureau). 12s. 6d. net.

Die Casting Machines and *Cemented Carbide Tools*. (Machinery Yellow Back Series). 3s. 6d. net. each.

"*Mitia*" *Carbide Tips and Tools Instruction Book*. (Firth Brown Tools Ltd).

ISSUE OF JOURNAL TO NEW MEMBERS Owing to the fact that output has to be adjusted to meet requirements, and in order to avoid carrying heavy stocks, it has been decided that the Journal will only be issued to new Members from the date they join the Institution.

IMPORTANT In order that the Journal may be despatched on time, it is essential that copy should reach the Head Office of the Institution not later than 40 days prior to the date of issue, which is the first of each month.

SECTION MEETINGS

The following meetings have been arranged to take place in April and May, 1949. Where full details are not given, these have not been received at the time of going to press.

April

1st WEST WALES SUB-SECTION. A film entitled " Patterns & Progress at Ebbw Vale," will be shown at 7-30 p.m.

4th YORKSHIRE SECTION. A lecture on " Industrial Politics " will be given by Mr. Lewis C. Ord, at the Hotel Metropole, Leeds, at 7-00 p.m.

5th BIRMINGHAM SECTION. An all-day visit will take place to the Austin Motor Co. Ltd., at Longbridge.

6th LUTON GRADUATE SECTION. The Annual General Meeting will be held at the Midland Hotel, Luton, at 7-00 p.m., followed by a Graduates' Evening from 7-30 p.m. to 9-00 p.m.

6th NOTTINGHAM SECTION. A lecture on " Industrial Lighting," will be given at the Victoria Station Hotel, at 7-00 p.m.

6th WESTERN SECTION. A lecture on " Rolled Steel Sections " will be given by Mr. G. Butler, at the Grand Hotel, Broad Street, Bristol, 1, at 7-15 p.m.

6th WOLVERHAMPTON SECTION. A lecture on " Centralisation *v.* Decentralisation in Industry," will be given by Mr. Lewis C. Ord, at the Wolverhampton Gas Co. Offices, Clarence Street, Waterloo Road, Wolverhampton, at 7-00 p.m.

8th EASTERN SECTION. A lecture on " Practical Approach of Research to Industry" will be given by Mr. H. W. Hobbs, M.I.P.E., at the Lecture Hall, Electric House, Ipswich, at 7-15 p.m.

9th YORKSHIRE GRADUATE SECTION. A Works Visit will take place to W. & T. Avery Ltd., Sherburn-in-Elmet, near Leeds, at 2-15 p.m.

11th HALIFAX SECTION. A lecture on " Production Design " will be given by Mr. B. G. Bowden, M.I.Mech.E., M.S.A.E., M.S.I.A., at the White Swan Hotel, Halifax, at 7-00 p.m.

April—*cont.*

12th BIRMINGHAM GRADUATE SECTION. A lecture on "The Efficient Inspection of Mass Produced Parts" to be given by Mr. J. Loxham, M.I.P.E., M.I.Mech.E., F.R.S.A., at the James Watt Memorial Institute, Great Charles Street, Birmingham, 3, at 7-00 p.m., preceded by a demonstration of equipment.

12th WOLVERHAMPTON GRADUATE SECTION. A lecture on "The Manufacture and Application of Sintered Carbides" will be given by Dr. E. M. Trent, at the Wednesbury Technical College at 7-15 p.m., and will be illustrated by a film entitled "The Wimet Age."

13th SHEFFIELD SECTION. A lecture on "How the Money Moves in Business" will be given by Mr. T. G. Rose, M.I.P.E., M.I.Mech.E., F.I.I.A., at the Royal Victoria Station Hotel, at 6-30 p.m.

14th LONDON SECTION. A lecture on "Mechanical Mishaps and Their Relation to Design and Workmanship" will be given by Mr. G. E. Windeler, M.I.Mech.E., M.I.Mar.E., M.Cons.E., at the Assembly Hall, Royal Empire Society, Northumberland Avenue, W.C.2, (Craven Street entrance), at 7-00 p.m.

14th LEICESTER SECTION. A lecture on "Balance in Line Production" will be given by Mr. W. Hewett, A.M.I.Mech.E., A.I.I.A., Int.A.M.I.P.E., in Room 104, Leicester College of Technology, The Newarkes, Leicester, at 7-00 p.m.

18th HALIFAX GRADUATE SECTION. A lecture on "The Production of All-Metal Bus Bodies," will be given by Mr. G. L. Hart, M.I.Mech.E., at the Technical College, Huddersfield, at 7-00 p.m.

20th BIRMINGHAM SECTION. A lecture on "The Education of the Production Engineer," will be given by Mr. T. B. Worth, M.I.P.E., A.M.I.Mech.E., A.M.I.E.E., at the James Watt Memorial Institute, Great Charles Street, Birmingham, 3, at 7-00 p.m.

20th EDINBURGH SECTION. A lecture on "Electronics in Industry" will be given by Mr. P. H. Briggs, B.Sc., at the North British Station Hotel, at 7-30 p.m.

20th LIVERPOOL SECTION. The Annual General Meeting—members only—and Presidential Address, will take place at the Exchange Hotel, Liverpool, at 7-15 p.m.

April—*cont.*

21st GLASGOW SECTION. A lecture on " Electronics in Industry," will be given by Mr. P. H. Briggs, B.Sc., at the Institution of Engineers and Shipbuilders in Scotland, 39 Elmbank Crescent, Glasgow, C.2, at 7-30 p.m.

22nd WOLVERHAMPTON GRADUATE SECTION. A Grand Easter Dance will be held at Beattie's Restaurant, from 8-00 p.m. to 12-00 p.m.

25th DERBY SUB-SECTION. A lecture on " Plastics " will be given by Mr. A. D. Whitehead, at the Art School, Green Lanes, Derby, at 7-00 p.m.

25th MANCHESTER SECTION. A lecture on " Social Function of Industry " will be given by Dr. A. Roberts, at the College of Technology, Manchester, at 7-15 p.m.

25th NORTH EASTERN SECTION. The Annual General Meeting, followed by the Chairman's Address, will be held at the Lecture Theatre, Neville Hall Mining Institution, Newcastle-upon-Tyne, 1, at 6-30 p.m.

27th HALIFAX GRADUATE SECTION. A lecture on " Modern Coal Face Machinery " will be given by Mr. J. W. L. Anderson, B.Sc., at the Technical College, Halifax, at 7-00 p.m.

28th SOUTH WALES & MONMOUTHSHIRE SECTION. A lecture on " How the Money Moves in Business " will be given by Mr. T. G. Rose, M.I.P.E., M.I.Mech.E., F.I.I.A., at the South Wales Institute of Engineers, Park Place, Cardiff, at 6-45 p.m.

May

4th NOTTINGHAM SECTION. A Presidential Address will be given at the Victoria Station Hotel, Nottingham, at 7-00 p.m.

4th WOLVERHAMPTON SECTION. A lecture on " Locks " will be given by Mr. H. G. Ramsell, M.I.P.E., M.I.Mech.E., at the Willenhall Evening Institute at 7-00 p.m.

10th WOLVERHAMPTON GRADUATE SECTION. A lecture on " Electro Static Spraying " will be given by Mr. J. Stribley, and Mr. W. H. Cockerill, A.M.I.P.E., A.M.I. Mech.E., at the Walsall Evening Institute, Wisemore School, Walsall, at 7-15 p.m.

19th LONDON SECTION. A lecture on " Modern Aspects of Centreless Grinding " will be given by Mr. A. Scrivener, M.C., M.Inst.B.E., at the Assembly Hall, Royal Empire Society, Northumberland Avenue, W.C.2 (Craven Street entrance), at 7-00 p.m.

GOBLIN AND GHOST JET PROPULSION ENGINES

by J. L. EDWARDS. *

Presented to the Southern Section of the Institution, November 12th, 1947.

The principle of the gas turbine has been known and understood for many years, but despite its mechanical attractiveness as a rotary unit, it was considered an impracticable proposition by the great majority of engineers owing chiefly to the high ratio of negative to positive work, and the metallurgical difficulties associated with materials required to operate for extended periods at high temperatures.

About 1926, however, consideration began to be given to the possibilities of a gas turbine power plant for aircraft propulsion, this particular application being selected owing to the considerable advantages which could be gained in an aeroplane from forward speed and altitude. The first provisional patent on a unit of this type was filed by F. Whittle in 1930 and was, in general, descriptive of gas turbine power plants as they exist today.

APPLICATION TO AIRCRAFT

In its application to aircraft, it was realised that the effect of forward speed or "ram" could be used to provide a certain proportion of the compression required, that the low temperature at altitude made possible a reduction in the negative work, and that the expansion through the turbine which was subject to turbine losses, was only a part of the total expansion.

Early in 1941 the De Havilland organisation was approached with a view to their entering the gas turbine field and, following a discussion between Major F. B. Halford, Engine Designer to the Company, and Sir Henry Tizard, Scientific Adviser to the Air Ministry, design work was put in hand in the autumn of that year.

No restrictions were placed on the Company as to the size or thrust of the proposed new engine, and the problem was approached in collaboration with the De Havilland Aircraft Division to see what power would be required for a single-seat fighter, to give a substantial improvement in performance over existing designs. It was finally decided that requirements would be met by an engine giving a thrust of 3,000 lb. and preliminary calculations were based on this figure. From this fundamental basis the Goblin engine emerged and in April, 1942, exactly 248 days after the first drawing was issued, the prototype engine passed its half-hour acceptance test. On the 15th April, after one or two minor mishaps,

* *of The De Havilland Company.*

The Institution of Production Engineers does not accept responsibility for any statements made or opinions expressed in any papers published in the Journal of the Institution.

it was run up to rated speed and developed the designed thrust of 3,000 lb. at a speed of 10,200 r.p.m. and a specific consumption of 1.233 lb. per lb. per hour, a most encouraging result.

Development was now pushed ahead as fast as possible, and in March, 1943, the first flight of the Goblin engine took place in a Gloster F9/40 aircraft from Cranwell Aerodrome. It is of interest to note that not only was this the first flight of the Goblin, but it was also the first flight of the prototype Meteor.

A considerable amount of useful information was obtained from this installation, but it was not felt that the full merits of the Goblin would be realised until it was installed in the aircraft for which it had been designed, namely, the Vampire. Unfortunately the completion of the prototype of this machine was delayed by other war commitments, and it was not until September, 1943, that the first flight of the Vampire took place. Results were all that could be desired and in May, 1944, the Vampire exceeded 500 m.p.h. at altitudes over 30,000 ft. and a thrust rating of 2,500 lb.

LIAISON WITH AMERICA During this time the closest liaison was kept with American activity; Allis Chalmers were associated with the De Havilland enterprise in this project and towards the end of 1943 two engines were despatched to the States for installation in the Lockheed XP80A, known better as the "Shooting Star." First flights of this aeroplane took place early in 1944, and it was actually the first aircraft to exceed a speed of 500 m.p.h. in level flight. In parallel with the Allis Chalmers activities, Curtiss Wright carried out experiments with a Goblin engine installed in a Grumman airframe, the XF/15C which, carrying both a reciprocating and a jet engine, could be used as a flying test bed.

By January 1945, the Goblin engine had been developed to the extent of completing satisfactorily the first official service type test of 100 hours at a thrust of 2,700 lb., and a speed of 10,000 r.p.m. In July a second type test was completed at an increased rating of 3,000 lb. and a speed of 10,200 r.p.m., thus establishing a standard for the present production Goblin engine.

Towards the end of 1943, it was realised that, versatile though the Goblin might prove, engines of even greater thrust would be required, and a second design similar in essentials to the Goblin was put in hand. The rating of this proposed new engine was 4,000 lb.

Before the design was complete, however, the planned static thrust had been increased to 4,400 lb., and by the spring of 1945 two prototype engines had been constructed. There were, however, radical differences between these two engines. The first, which was designed to meet the requirements of a specific manufacturer, had fourteen combustion chambers and a diameter of 57 in. It has

since been dropped. The second was a re-design intended to reduce diameter ; it was only 3 in. larger than the Goblin and the number of combustion chambers was reduced to ten. This second design, subsequently known as the Ghost, first ran in October 1945, developing its design rating of 4,400 lb. but by December of that year the thrust had been increased to 5,000 lb. Up to the present time this engine has completed a considerable amount of running, and experimental flying has been carried out in the Vampire and, just recently, in a Lancastrian where two Ghost engines have been installed in the outboard nacelles, retaining the Merlins inboard.

DEVELOPMENT OF GOBLIN AND GHOST

In the following paragraphs an attempt has been made to trace the development of the De Havilland Goblin and Ghost engines from their inception to the present day. Most of the descriptive matter relates to the Goblin, which is inevitable since this was the first engine and, therefore, suffered all trials and tribulations associated with the initial development of any new machines. Much of the experience gained on the Goblin has gone into the Ghost, and the general development of the two engines has to a large extent proceeded on parallel lines. Naturally each has its idiosyncrasies, but these are ironed out in the normal course of events and no great stress will be laid on them ; in any case it would not be possible to dwell at great length on any detail, but it is hoped that the writer will be successful in conveying a general picture of the work carried out.

GENERAL CONSIDERATIONS

In general the jet and airscrew function in the same way. Each accelerates a mass of air in a rearward direction and, in so doing, produces a forward reaction on the aircraft which causes motion. A state of equilibrium is reached in each case, when the forward thrust or jet reaction equals the rearward drag on the aeroplane, under which conditions the aircraft moves in level flight at constant speed. Gravity effects due to climb or dive will automatically reduce or increase the forward speed, until equilibrium is again reached.

The difference between the two methods is that the airscrew moves a large quantity of air accelerating it through a fairly narrow speed range, whereas the jet engine moves a small quantity of air through a wide speed range.

If, in any installation, the air leaving the airscrew or engine has a velocity relative to the surrounding air, then this energy in the wake represents a loss in power ; ideally the air leaving the unit should have no velocity relative to the surrounding air, when there would be no loss to the wake and all the energy would be utilised in propelling the aeroplane. Unfortunately the air entering the airscrew or engine is travelling relative to the aeroplane ; if it now

has to leave at the speed of the aeroplane as well, then there is no change in the velocity of the air passing through the unit and there is, therefore, no thrust. Admittedly there are no wake losses and the propulsive efficiency is 100%, but since this represents a dragless aeroplane moving at uniform speed it is obviously a purely theoretical conception.

From the above argument it is, nevertheless, possible to draw the conclusion that the more closely the speed of the aircraft approaches the speed of the slip stream, the more closely does the propulsive efficiency approach 100%. Hence, for a given thrust, the greater the mass flow, the smaller will be the speed range over which the air is accelerated, and the closer the approach of the slip stream to the aircraft speed. We thus see that with the large mass of air accelerated by the airscrew this method of propulsion will be more efficient than the jet, where a small mass of air is employed.

If we were to consider the problem from the point of view of propulsive efficiency only, the propeller is the better proposition. Unfortunately the propeller, as an instrument for moving air, has its limitations. At low speeds it is fairly good, having a maximum efficiency of the order of 85%. As the speed increases, however, two troubles become manifest ; first the blades tend to stall and, second, the blade tips approach the speed of sound. The first of these snags can be largely overcome by the use of variable pitch propellers ; the second can be delayed by modification to the blade profiles, but ultimately the effects of compressibility on the blades in reduction of lift and increase in drag, causes the efficiency to drop off very rapidly, until at speeds of the order of 500 m.p.h., the overall efficiency is so low that thoroughly uneconomical powers would have to be developed by the prime movers if the specified performance were to be obtained.

This disadvantage is not experienced by the jet propulsion unit and as the forward speed rises and the speed of the aeroplane approaches more and more closely to the speed of the jet, so the unit becomes more efficient, until at speeds of 500 m.p.h. and over it is the only practical way of obtaining increased thrust. At the same time it must be borne in mind that at speeds below 500 m.p.h., including take-off, the airscrew is the more effective. As an example, the take-off thrust of the De Havilland Ghost is 5,000 lb., which compares with the take-off thrust of say, a Sabre, of some 10,000 lb. This disadvantage of low take-off thrust can, in a measure, be overcome by the use of water methanol injection, rocket assisted take-off, or thrust augmentation. Alternatively, if the mechanical advantages of a gas turbine are desired coupled with the low speed characteristics of the airscrew, then a gas turbine prime mover can be used to drive a propeller.

Accepting the superiority of the jet engine at high speeds, a number of other important effects must be considered, the principal of which are forward speed and altitude.

The effects of forward speed are twofold. In the first instance when we consider that the effective thrust is equal to the change in momentum of the air passing through the unit, an increase in the entry speed without a corresponding increase in the exit speed results in a reduction in the change of momentum and reduced thrust. On the other hand, however, if by a suitable design of ducting the velocity energy in the air at entry to the engine can be converted to pressure energy, then a proportion of the compression is already accomplished, which means that the effective compression ratio of the blower is increased, or the amount of negative work required for a given compression ratio, is decreased.

Either way the energy available for propulsion arises. In practice the combined effect of these two conflicting influences is to give a slight drop in static thrust up to about 400 m.p.h., after which the thrust rises until the static thrust is completely recovered at a speed of 600 m.p.h.

The effects of altitude are three-fold. The decrease in density reflects adversely on the mass flow for a given engine speed, but the effect of decreasing temperature is such as to increase the engine efficiency, by a reduction in the amount of negative work required for a given compression, whilst the reduction in ambient pressure increases the pressure drop across the turbine. The nett result is a decrease in the thrust but an increase in efficiency, resulting in an improved specific fuel consumption.

Summarising, we see that if we require an aeroplane which will fly slowly, the economical arrangement is to use a propeller, driven either by a reciprocating engine or a gas turbine. If, on the other hand, we require speed and economy, then the only practical arrangement is the jet propulsion unit which operates most efficiently when flying high and fast.

THE JET PROPULSION UNIT Essentially the gas turbine cycle is similar to the reciprocating engine cycle, the air being drawn in, compressed, heated and expanded. The difference between the engines is that in the gas turbine each of the above processes is continuous, and takes place in a different part of the engine, whereas in the reciprocating engine the processes are consecutive, and take place in the same part of the engine.

The problem of constructing an engine to work on the gas turbine cycle resolves itself into some means of compressing the working fluid, adding heat to it, and then converting this heat to mechanical work. Many methods are open to us. Reciprocating compressors, centrifugal or axial compressors, or any combination thereof, are

practicable. They can be driven from an outside prime mover, such as a normal reciprocating engine or a gas turbine, or even steam turbines have been suggested. The necessary heat can be supplied by passing the air through a heat exchanger and supplying heat from an external source by mixing the air supply with a supply of heated gas, or by burning fuel directly in the air stream and supplying the air and combustion products to the jet pipe. The problem is not how to produce the supply of heated air, but to select a method which will give the best results in the most economical manner.

From an aircraft installation point of view a rotary unit is definitely preferable. It must be as compact and as light as possible, and it must be efficient. This rules out such schemes as reciprocating compressors driven by external prime movers and there is little doubt that the best arrangement is that which has been generally adopted, namely the use of a rotary compressor driven by a gas turbine, supplying air to a combustion chamber or chambers in which fuel is burnt, the products of combustion then being supplied to a jet pipe which converts the pressure energy into velocity energy.

In selecting the best arrangement of compressor and combustion chamber, real difficulty was encountered. Very little reliable information was available when the De Havilland Company started work on turbo-jet design early in 1941, and whilst the general layout of the compressor combustion system, turbine and jet pipe was fairly obvious, the details required careful consideration.

COMPRESSOR The two basic types of rotary compressor were available, the centrifugal and the axial. Of these two varieties the axial flow compressor was theoretically superior to the other, in that higher compression ratios were available.

At the same time, however, very little running experience was available and it was known that compressors of this type were prone to stalling troubles ; furthermore, the design was inclined to be heavy and bulky, a serious consideration when the installation of the unit in a single-seater fighter was envisaged. It was also known that the German jet propulsion engines employed the axial type of compressor, and it was suspected that the German engineers were having some trouble with this unit. As regards the centrifugal compressor, however, an enormous mass of both theoretical and practical information was available; it had already been used with success on turbo-jet installations and had been used for engine superchargers for many years.

In view of these considerations, it was felt that the incorporation of an axial compressor in the design of the first De Havilland turbo-jet engine would be a rather risky undertaking, as the development

work required to bring satisfactory results might be so extensive as to prevent the production of the engine in quantity for a very long time. Obviously in view of the conditions prevailing in 1941 this was an untenable situation and thus it was decided to use the centrifugal compressor, despite its lower theoretical performance.

CENTRIFUGAL UNIT Two types of centrifugal unit were available. The first was that employed by Whittle in his engines, and utilised a double-sided impellor. The second was an entirely new departure for jet engines, and employed a single-sided impellor. Considering the two designs on the basis of static engine thrusts with unrestricted air intakes, it appeared that the double-sided impellor would provide a smaller diameter engine than the single-sided for the same thrust. This would be economical in that a smaller nacelle could be used, and a lighter installation would result. Again, the manufacture of a single-sided impellor was a rather difficult undertaking, and would require the installation of special machinery. Furthermore, the large diameter and big blades might introduce mechanical and vibration troubles which could not be foreseen.

When installation in the aircraft was examined, however, the apparent advantages of the double-sided impellor were not so obvious. An installation of this kind required the provision of air intake passages to both sides of the impellor. Whilst the airflow to the eye of the front was fairly straightforward, air to the rear side of the impellor had to flow over the outer diameter of the diffuser casing, in between the combustion chambers, and turn through 180° in passing through the compressor. This led to friction and eddy losses, reduced the airflow to the rear of the compressor, set up unsteady conditions of both pressure and temperature, and resulted in unequal air delivery from the two sides of the impellor. Furthermore, the provision of an annular air passage around the diffuser casing negatived the advantages which had apparently been gained from the smaller engine, and the ultimate nacelle size for the double-sided impellor was actually no smaller than for the single-sided impellor.

A consideration of the installation of an engine with a single-sided impellor showed the enormous advantages which would be obtained. In the first place it was not necessary to provide annular air spaces around the outside of the impellor, thus keeping the nacelle size to a minimum ; secondly, the air intake could be made of ample size and could be blended very nicely into the framework of the aeroplane giving maximum efficiency with minimum eddy and friction losses, resulting in a smooth and steady flow of air into the eye of the impellor, and thirdly, the fact that the air had

not got to be led between the combustion chambers enabled a much more compact combustion system to be designed.

Preliminary layouts were, therefore, prepared, utilising a single-sided impellor. As the work progressed the extremely smooth airflow through the whole unit became increasingly obvious. The air, led through carefully designed intake passages, flowed smoothly into the eye of the impellor passed with a minimum number of bends directly to the combustion chambers, where heat was added by the direct injection of fuel, and thence passed through the turbine nozzles and blades to the jet pipe.

No sharp bends or unequal air distribution effects on the impellor were present, and the performance obtained on the test bed would quite possibly be bettered in flight when the full benefit of the ram was obtained. With the alternative design of double-sided impellor the test bed performance with open intakes would almost certainly not be reproduced in flight and, furthermore, ram effects would vary considerably between the two sides of the impellor, thus further accentuating the unequal air flows.

As it has always been the policy of the De Havilland Company to design the engine for the aeroplane, there appeared no argument as to which of the two designs was preferable, and despite considerable adverse criticism the single-sided impellor was adopted, and the design proceeded.

From a performance point of view this decision has been amply justified, but it has been by no means plain sailing. In the first place the manufacture of an impellor 31 in. in diameter and weighing some 110 lb. in its fully machined condition was a formidable proposition, ultimately solved by the use, in the early days, of a Keller copying machine, and subsequently a modified form of Cincinnati Profile Miller. The work involved can be imagined when it is realised that the forging weighed about 400 lb.

Generally speaking the design of this component has remained unchanged. In the early days, however, some impellor failures occurred and on the advice of High Duty Alloys a change was made in the silicon content of the alloy with a view to improving the ductility, and an improved casting technique was adopted whereby the production of impellors from single "cheeses" was discontinued in favour of the continuously cast ingot.

TESTING OF THE IMPELLOR

The independent testing of an impellor of this size is clearly a difficult matter because of the large power input required, but under the auspices of the M.A.P. and with the help of Power Jets Ltd., a spare steam turbine at Northampton was fitted with a gear box and coupled to a Goblin compressor. The general arrangement is shown in Figure 4. With this set-up it was possible to run the compressor at 10,000 r.p.m. under open intake

conditions, before the available 6,000 h.p. set a limit to further increases, though an increase to 11,000 r.p.m. was possible if the intake were throttled. The results of these tests, which showed an isentropic efficiency of 82% based on the temperature rise and the pressure ratio between intake and outlet, have been exceedingly valuable in determining the best combination of compressor and turbine so that each shall run at maximum efficiency, and it was exceedingly unfortunate that the tests should have been terminated with unexpected suddenness by a rub between the impellor and the casing.

Recently an examination of the stresses arising in the impellor, due to resonant vibration set up by the passage of the impellor vanes through the uneven pressure regions set up by the four intake struts and the sixteen diffuser vanes, has been carried out, using wire strain gauges. Figure 5 shows the fatigue failures which occurred on an impellor after a considerable amount of running under fourth order resonant conditions, and Figure 6 shows the slip ring assembly used for picking up the strain gauge responses and transmitting them to the amplifying and recording gear.

This work resulted in a slight modification to the leading edge of the impellor which raised the fundamental flapping node of vibration, the modification consisting of chamfering back the leading edge of the entry portion. This change also had the unexpected effect of increasing the thrust and reducing the jet pipe temperature, a result ascribed to the improvement in the Machine Number at the outer portion of the entry vanes, similar to the "sweep back" of the wings of an aircraft.

COMBUSTION Combustion chambers presented an entirely new set of problems. As with the compressor, two general alternatives were available, namely the completely annular chamber supplied with fuel from a series of symmetrically placed burners, or a series of individual chambers each fed by an individual burner. The annular chamber was attractive in that it was easy to make, light, and would probably provide an even flow of gas through the turbine and jet pipe.

On the other hand development promised to be exceedingly difficult and the reproduction of engine conditions on a rig would involve complicated and heavy apparatus, and results might well be misleading. This meant that all development would have to be carried out on an engine, where, of course, it would be subject to the availability of test facilities, and would inevitably tie up development engines which could well be used for other purposes. Again, the annular chamber was a comparatively unknown quantity and it was impossible to predict just how much development would be required to produce a satisfactory unit.

The individual combustion chamber, on the other hand, had been developed to a certain extent by Whittle and the R.A.E. and some information was available on which initial designs could be based. It was not difficult to produce a rig on which individual combustion chambers could be tested without having to run an engine, and it would thus be possible to carry out intensive and purposeful testing in a comparatively short space of time, and without tying up test capacity and development engines. The principal disadvantage was the extra weight and cost of manufacture, and the tendency for the gas flow over the turbine nozzle ring to be a little uneven.

Taking everything into consideration, it was felt that the Company were not justified in attempting to develop the annular chamber, and the more orthodox design employing single chambers was adopted.

The initial work was carried out in conjunction with the R.A.E. and a preliminary design was prepared based on information in their possession, obtained from experience on Whittle engines. Specimen combustion chambers were made up and initial test work started on a low density test rig installed in one of the dispersal stations. For three months every effort was concentrated on developing a chamber which would give reasonable efficiency and flame stability, and ultimately, after about 90 modifications had been effected on the original design, satisfactory results were obtained, and a full set of chambers was put in hand for the prototype engine.

Since these early days, conception as to what constitutes a well designed combustion chamber has radically altered, rig work and testing technique has improved and Figure 7 shows a comparison between the original "stub-tube" chamber and the present "flower pot" chamber. The requirements of a good combustion system are, as in most things, conflicting. We require to keep the pressure drop between entry and exit as low as possible in the interests of general performance; mixing should be perfect, and the gas should be delivered to the turbine at an even temperature and uniform velocity; flame length should be short so that the overall dimensions of the combustion chambers are as low as possible. Short flames and uniformity of delivered gas go with good mixing, and good mixing is helped by high pressure drop. Slowly, therefore, a chamber has been evolved which combines the mixing and chemical properties of the old chambers without their multiplicity of projections and bits and pieces, with a streamlined form giving even and smooth gas flow with low pressure losses. Even yet, however, there is a long way to go in the development of a combustion system which will fulfill all the exacting requirements of the modern gas turbine power plant.

TURBINE The third major component, namely the turbine, driving the compressor, left very little choice as to its form ; the overall dimensions being determined by the general dimensions of the engine. The major problem was metallurgical, and with one exception all development work has been in that category. After the first four engines had been built, the chord of the rotating blades was increased by 30% and their number decreased proportionately. The object of this change was to strengthen the blades by thickening them—particularly at the roots. As a result the gas bending stress was reduced from 6.6 tons/sq. in. to 2.8 tons/sq. in. at full duty, and the natural frequency of vibration was raised. Aerodynamically the blades were similar to the narrow chord type and the performance was, in fact, identical.

The first engines were fitted with turbine blades and discs made from Firth's Rex 78, the finest austenitic steel that was then available.

A programme of experiments with heat sensitive paints indicated that the disc could be held at a temperature well below the gas stream, and that the centre temperature, where the stress was highest, was below 250° C. These conditions reinforced by theoretical work, indicated that a ferritic type of steel could be used for the discs in place of the austenitic material which had at first been thought essential. A suitable ferritic material offered advantages in the way of improved mechanical strength, enabling a lighter disc to be made, reduced alloy content and hence cheapness, greater ease of machining and improved thermal properties resulting in reduced temperature stresses.

For some time the blade material was retained as Rex 78, but after some 1,400 hours' testing increases in the rating of the engine rendered a change to Nimonic 80 alloy advisable. Incidentally, there has only been one failure of a turbine blade in flight, and in this case the pilot throttled back and continued flight for about ten minutes before landing safely at his home aerodrome. Apart from other things, this was a very useful piece of information, as grave doubts had been experienced as to the effect of a blade failure on the engine structure and mountings, the centrifugal force exerted, due to out of balance, being of the order of one ton.

ROTATING ASSEMBLY The main rotating assembly (Fig. 8) comprising the impellor, turbine and main shaft is carried on two ball-bearings, the front bearings being held in a fixed housing and designed to carry the end thrust of the assembly, and the rear bearings running in a sliding housing which moves to allow for expansion effects. A considerable amount of research, carried out in conjunction with the bearing manufacturers and the N.P.L., has gone into the production of satisfactory ball-bearings for the

onerous duties imposed by the gas turbine application, the best compromise ultimately being found in the use of ball located phosphor bronze cages and increased diametral clearances coupled with scrupulous inspectional standards.

Balance of the assembly is assured by the balancing of the impellor on a Gisholt Dynetric Balancing Machine (Fig. 10) two or three times during the scurfing operations, the static balancing of the blade and disc assembly on a specially designed Avery moment balance, and the final dynamic balancing to very fine limits of the whole rotating assembly. The degree of balance is so fine that the slightest irregularities in the ball-bearings render accurate balance to the limits specified, impracticable. A final check on balance is carried out on the test bed where the maximum vibration amplitude permitted at full duty is $\pm$.001 in.

FUEL SYSTEM AND STARTING The first runs of the Goblin engine were made with spring-loaded burners which opened their ports as the fuel flow increased. This provided a good fuel pressure for idling without excessive pressure at full duty. As, however, there was a possibility of the sliding parts of the assembly sticking in operation and throwing the combustion chambers out of balance, it was decided to standardise on the Simplex type of burner with a simple, fixed orifice, and initial flights were carried out with an arrangement of this sort. A fuel pressure of 800 lb./sq. in. at full duty was required, but after some initial trouble with pipes and joints, this has been found quite satisfactory.

The starting of the engine involves the use of a fairly complicated fuel system, so interconnected with the ignition and starter motor circuits as to allow the engine to be spun up to a speed where sufficient air will flow through to ensure ignition before any fuel is admitted. An automatic valve then opens and allows fuel to be injected into the burners from a fuel accumulator which has built up a pressure of some 40 lb./sq. in. Operation of the igniter plugs starts combustion, but it is still necessary to assist the engine up to a speed of 1,500 r.p.m. before it can be accelerated under its own power up to the idling speed of 3,000 r.p.m.

The illustration (Fig. 11) shows the layout of the fuel and ignition systems. Fuel is fed from the aircraft fuel system either by gravity or by pressure pump to the engine fuel pump. This is an adaptation of the Dowty hydraulic pump with seven plungers reciprocating in a cylinder block rotating around a central stationary shaft containing the suction and delivery ports. The pistons are operated by aluminium slippers held against an eccentric ring by centrifugal force. The pump is rated at about 650 gal./hr. at a pressure of 800 lb./sq. in. at its maximum speed of 2,500 r.p.m. corresponding to an engine of 10,500 r.p.m.

The whole of the fuel delivered by the engine fuel pump passes through a fuel control box containing a metering orifice, the area of which is controlled by a taper needle, operated from a lever in the pilot's cockpit. The contour of the needle is so arranged that a substantially linear response exists between the movement of the throttle lever and the engine thrust, thus giving approximately even increments of movement of the throttle for equal increases in thrust.

As the altitude increases and the density of the air diminishes, the fuel requirements of the engine decrease, and the engine speed must be controlled by constant manipulation of the throttle. To overcome this and to obviate the necessity of constant supervision by the pilot, an automatic altitude control known as the barostat has been introduced, which has the effect of reducing the fuel pressure and, therefore, the fuel flow, as the altitude increases. The barostat is adjusted to give constant speed without the adjustment of the manual control, and has proved very satisfactory.

After leaving the fuel box, the fuel passes to a high pressure distribution valve and an overspeed governor. This latter unit interposes a restriction in the fuel line if a safe speed is exceeded and thus restricts the fuel flow. Thence the fuel passes to a fuel accumulator, an automatic starting valve, an automatic pressure switch and into the burner supply ring.

The high pressure distribution valve is operated by a separate lever in the cockpit, and serves to control the flow of fuel from the fuel control box. In the open position it permits the fuel to pass into the burner supply system, whilst in the closed position it cuts off the burner supply line, at the same time connecting the discharge from the fuel control box and the burner supply line to drain.

The fuel accumulator is provided to make sure that a sufficient quantity of fuel is available for efficient starting. This, in conjunction with an automatic starting valve which is set so that the accumulator cannot discharge its contents into the burner distributor rings until the fuel pressure has risen to about 40 lb./sq. in., assures that the fuel is at the correct pressure for starting. An automatic mechanical catch is provided in the automatic starting valve to prevent it closing due to vibration or shock, or when the fuel pressure falls to the low values associated with flight at high altitudes. This mechanical catch is automatically withdrawn when the high pressure distribution valve is closed.

The automatic pressure switch is provided to prevent the full power of the starter motor being applied until there is fuel pressure in the burner ring, indicating that fuel is being delivered to the burners.

TESTING Figure 12 shows the Goblin engine mounted on one of the first test beds. Testing facilities were, of course, non-existent when the Company embarked on this project but it was found possible to convert two Gipsy piston engine test beds in time for the prototype Goblin engines. The engine was mounted on a cradle suspended from a roof by four swinging ties, movement of the cradle in a forward sense being prevented by a hydraulic plunger which transmitted pressure to the cabin and provided a measure of the thrust developed.

A considerable amount of testing has been carried out in these tunnels, but in many ways they are unsatisfactory for the job and Figure 13 shows the latest type of production test bed.

In this case the engine is mounted on a trolley running on a special ball-bearing arrangement below floor level, which improves accessibility and facilitates engine changing. Thrust is recorded hydraulically as before, and the exhaust passes through a silencer mounted inside a sound-proofed exhaust tunnel. A bell-mouthed intake is used as a measuring orifice, and is mounted on the engine so that the true nett thrust is measured. Speed is recorded by the use of a stroboscope driven from the engine on test, and illuminated by a flashing neon lamp operated by a precision tuning fork. Because the thrust/speed characteristic is very steep at full duty, it is essential to measure the r.p.m. with far greater accuracy than suffices with a piston engine.

The Goblin engine has been tested at extremes of temperature between — 40° and + 40° C., but one of the most interesting tests carried out was at the conclusion of the war when an opportunity was given us to test an engine in the B.M.W. altitude test cell at Munich. Figure 14 shows the Goblin engine in the test chamber, which was 12 ft. in diameter and could be evacuated to pressures equivalent to an altitude of 50,000 ft. The supply of air to the intake could be refrigerated to — 70° C. if required. A diagrammatic representation of the plant is shown (Fig. 15), indicating pressures and temperatures at various points in the circuit. In brief, air is compressed, cooled in an arrangement of heat exchangers and then passed to a turbine ahead of the altitude test chamber. By adjustment of the flow through this turbine the temperature of the air entering the test chamber could be varied between — 70° and 50° C. The blast equivalent to the speed of flight is obtained by regulation of the compressor supplying the cell in relation to the air consumption of the engine and the capacity of the exhauster pumps which evacuate the altitude chamber. The exhaust from the engine is cooled by water spray and in heat exchangers before it is compressed and released to atmosphere.

Altogether over 70 hours of testing were completed at Munich and the information obtained has been invaluable.

A representative set of non-dimensional curves is shown (Fig.16), but these have been so arranged that they are representative of sea level conditions ($P_a = 14.7$ $T_a = 288°$ K.). These curves demonstrate the reasoning in the earlier part of the lecture as they show the effect of forward speed on the engine performance. At the lower speeds of rotation nett thrust is not greatly affected by the forward speed, and in fact falls off due to the adverse momentum change at the air intake. At maximum r.p.m. this fall-off is more than recovered by the beneficial effects of ram in increasing the mass flow through the engine, and at the highest speeds of revolution the engine is considerably more powerful than its nominal 3,000 lb. thrust on the test bed would indicate.

CONCLUSION The foregoing paragraphs cover the design and development of the Goblin engine. The bigger brother of the range, the Ghost, has in so far as general considerations go followed the pattern set by its predecessor, but where the Goblin was initiated in the stress of the early days of the war, the Ghost has had a more leisurely birth, and its characteristics have been considered from the point of view of civil as well as military requirements. Emphasis has been laid on performance combined with reliability and low engine weight, combined with efficiency and fuel economy, and in these respects it is a definite advance on the Goblin.

As far as further advances go, however, the engine performance or the engine reliability, whichever is desired, can only progress as the metallurgist progresses, for the crux of the whole engine lies in the development of suitable heat-resisting materials which will withstand the high temperature necessarily associated with efficiency. At the moment the ability of materials to withstand increasing temperatures without fatigue or appreciable creep sets a limit to what can be done.

The advent of the jet propulsion engine has increased the speeds of aircraft by some 200 m.p.h. in the last six years and has brought the aircraft designer face to face with the problem of compressibility. The solution of this problem will be by no means an easy task and will involve both aircraft and engine designers in a tremendous amount of fundamental research work and intensive detail development. One such attempt is shown in Figure 17 which depicts the DH/108, an experimental tailless aircraft with wings swept back to minimise the onset of critical conditions, and fitted with an uprated Goblin engine. The performance of this machine is considerably better than the Vampire.

In conclusion, it is still of interest to look back on the progress

of jet propulsion engines produced in this country as compared with those produced in Germany during the war. The dominating feature of the German engine was the use of the axial compressor which apparently gave them endless trouble, and though they did produce an engine which gave a good performance, the casualty rate among pilots was very grim, and the time taken to produce a reliable engine was so great as to preclude their production in sufficient quantity in time to have any influence on the course of the war. Despite statements to the contrary, German engines were never as good as those produced in this country ; they had a specific weight some 30% greater, a specific fuel consumption about 20% greater, developed about 25% less thrust, and had a service life only about one-third of the life of the standard British unit.

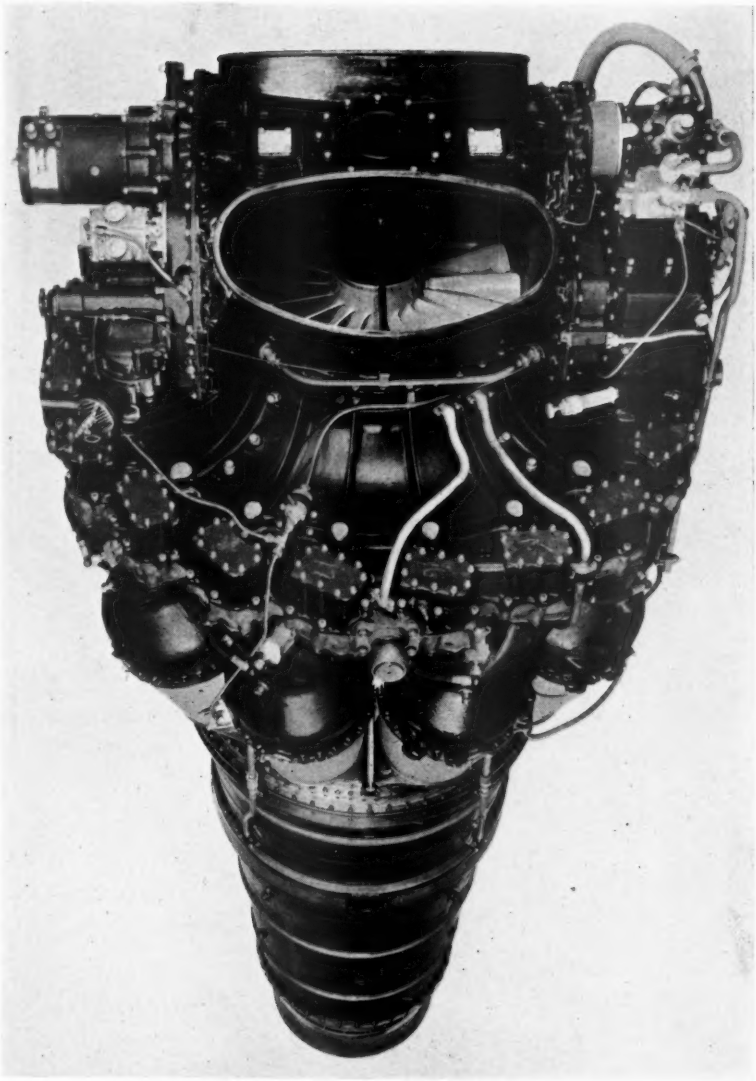


Fig. 1. De Havilland Ghost Jet Propulsion Engine.

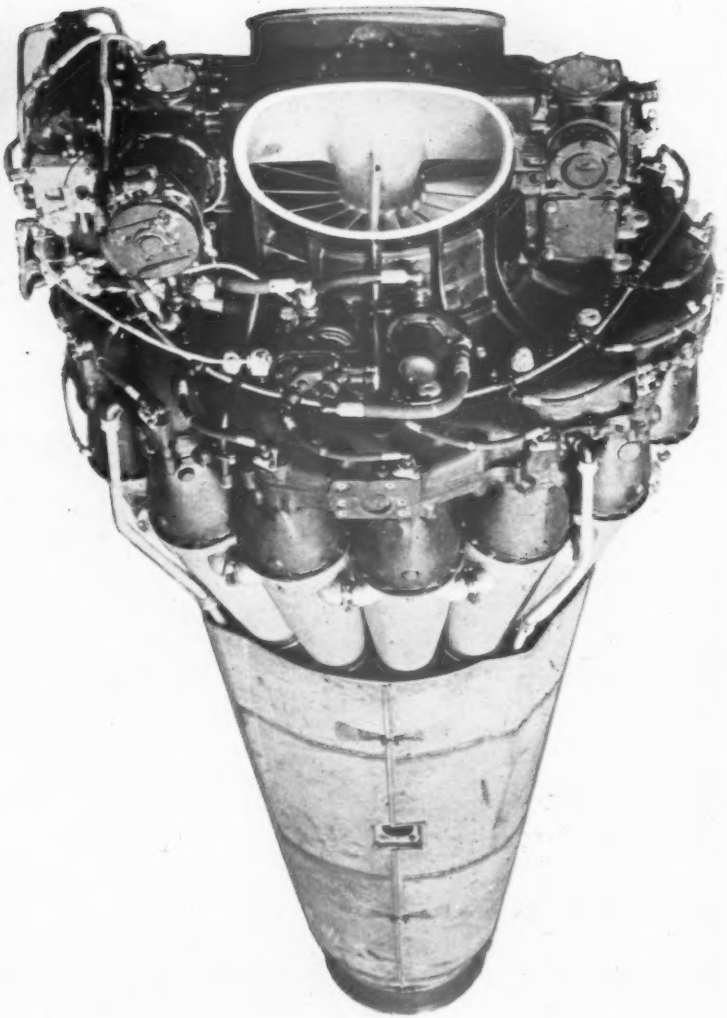


Fig. 2. Goblin II engine.

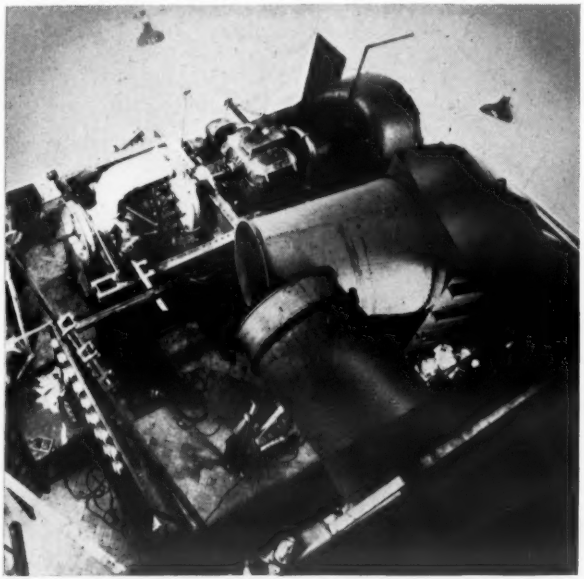


Fig. 4. Compressor test rig at Northampton.

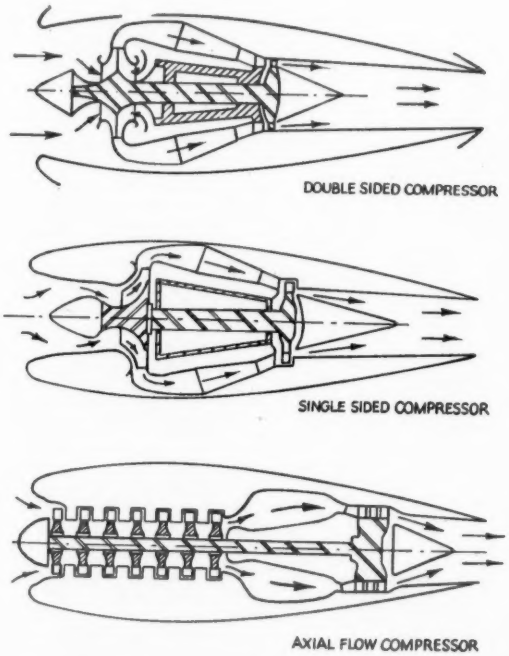


Fig. 3. Different arrangements of compressors, showing air flow.

Fig. 5. Fatigue failure of impellor blades.

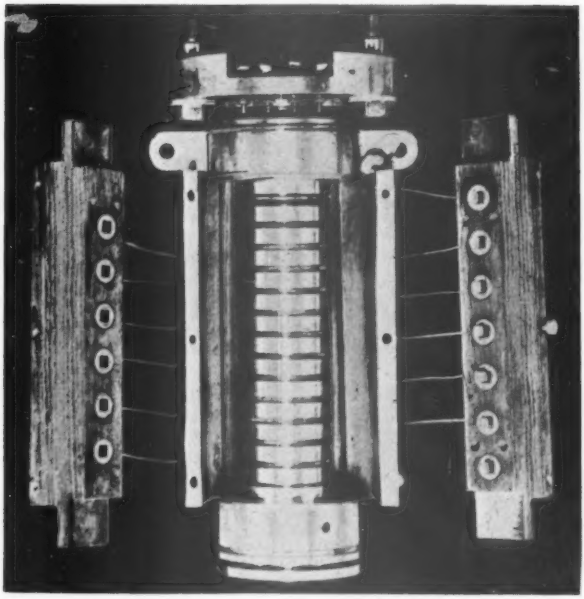


Fig. 6. Slip ring assembly

Fig. 7. Comparison between current "flowerpot" chamber (left) and the design originally employed.

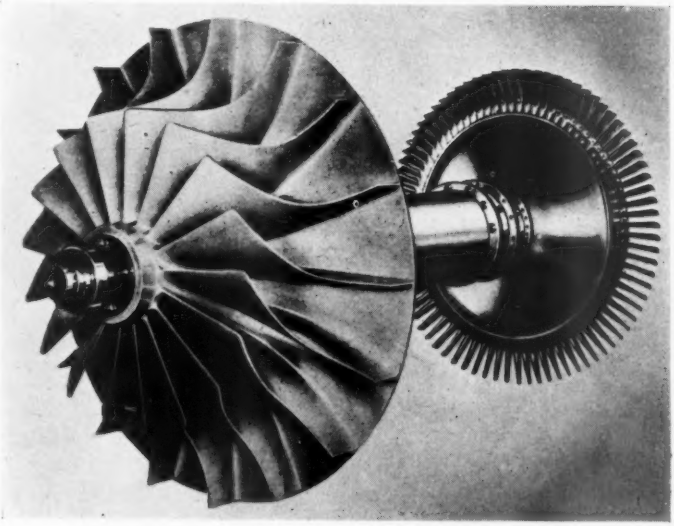


Fig. 8. Main rotating assembly, Goblin engine.

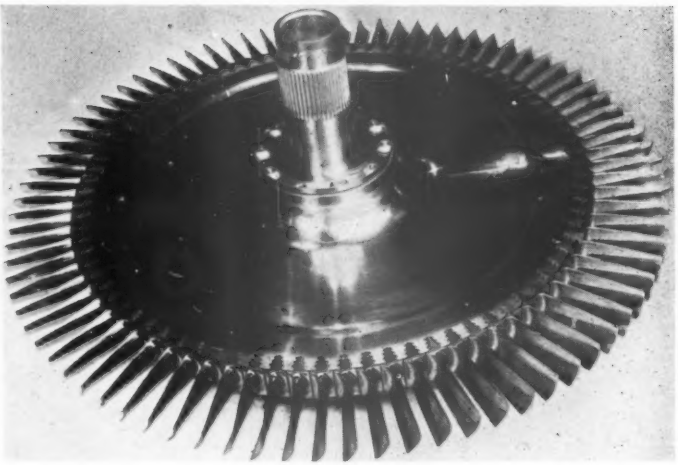


Fig. 9. Turbine rotor Goblin engine.

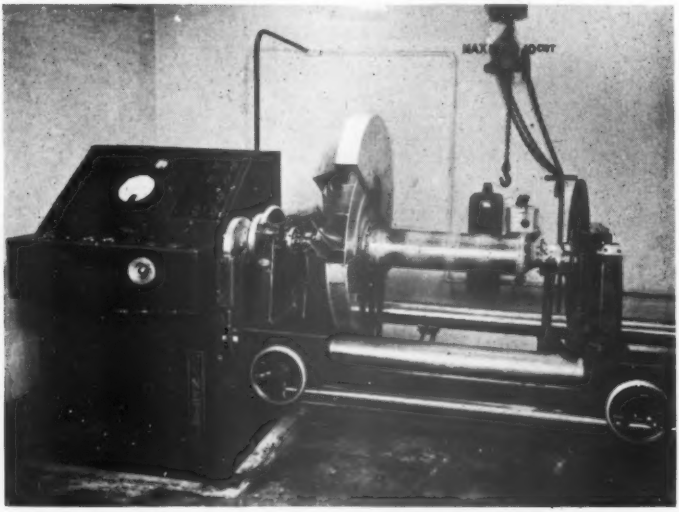


Fig. 10. Rotating assembly on Gisholt "Dynetric" Balancing Machine.

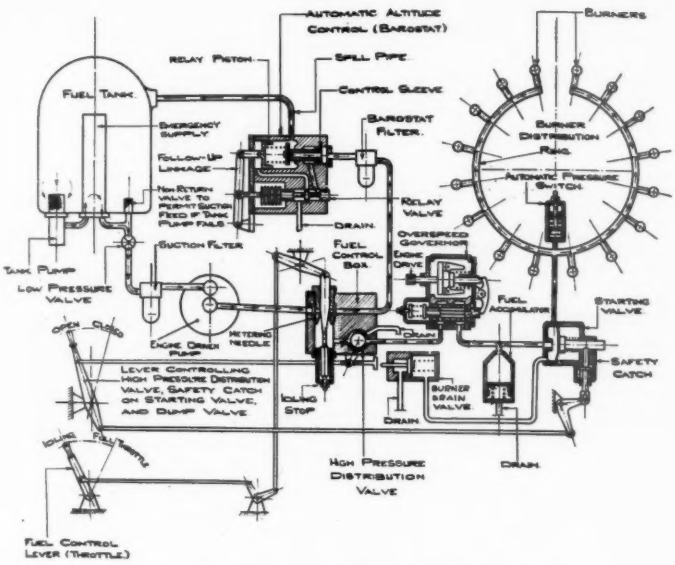


Fig. 11. Diagrammatic layout of fuel system.

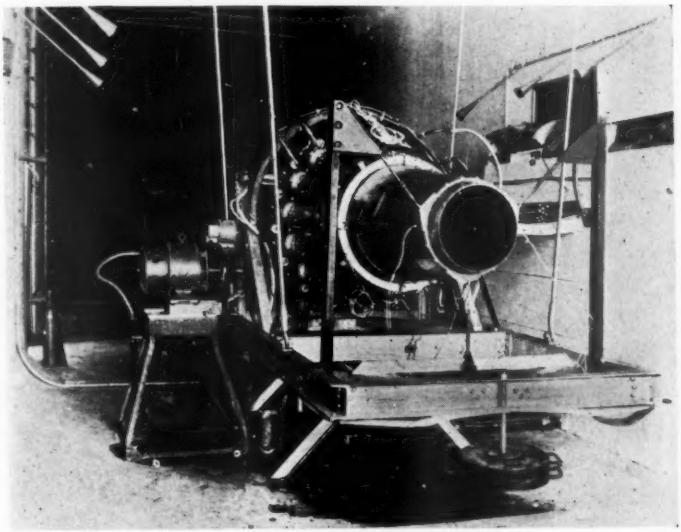


Fig. 12. Goblin mounted on converted Gipsy engine test bed.

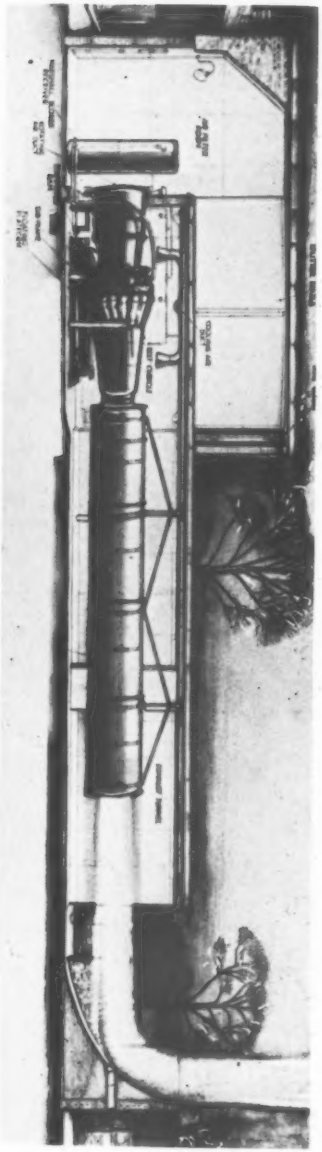


Fig. 13. Latest type of production test bed.

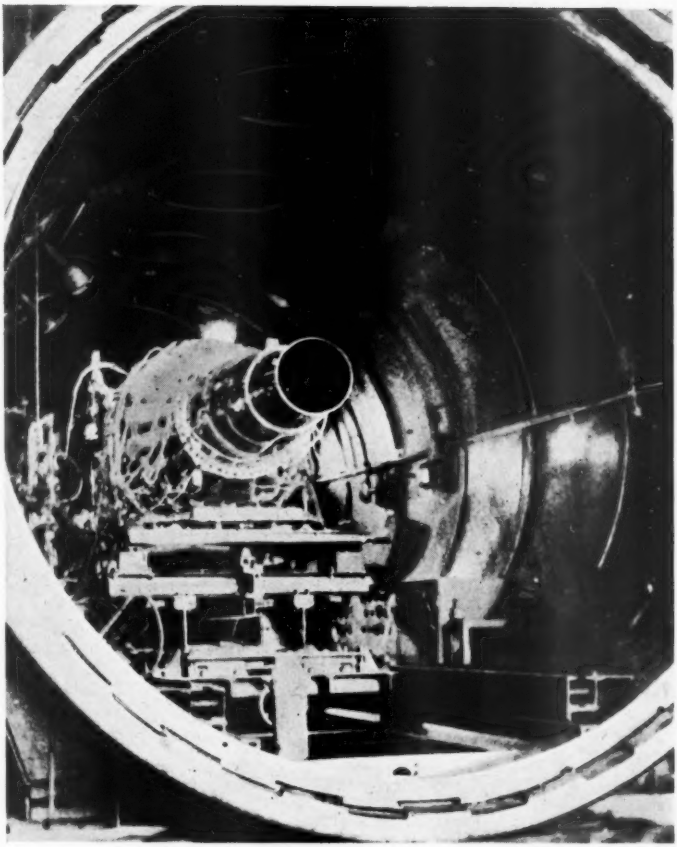


Fig. 14. Goblin engine in high altitude test cell at Munich.

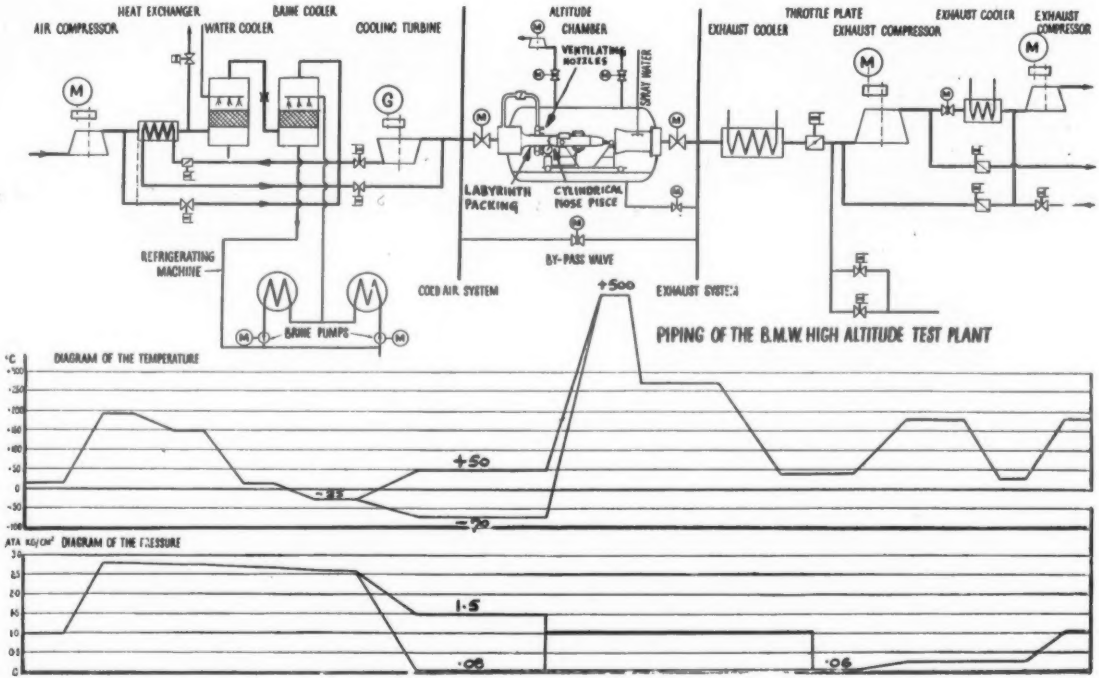


Fig. 15. Diagrammatic layout of Test Plant at Munich.

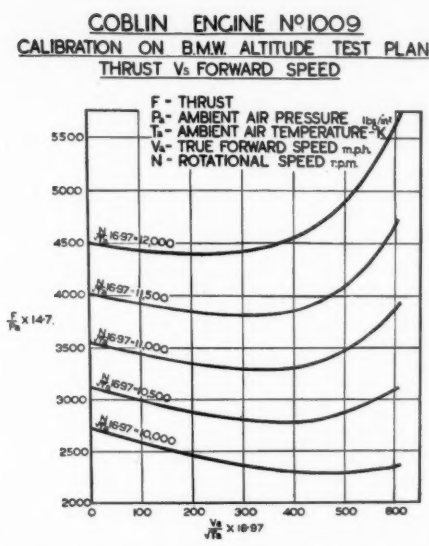


Fig. 16. Non-dimensional curves plotted from Munich test results.

Fig. 17. D.H.108 experimental aircraft, powered by an uprated Goblin engine.

Fig. 18. Lancastrian fitted with Ghost engines in outboard nacelles.

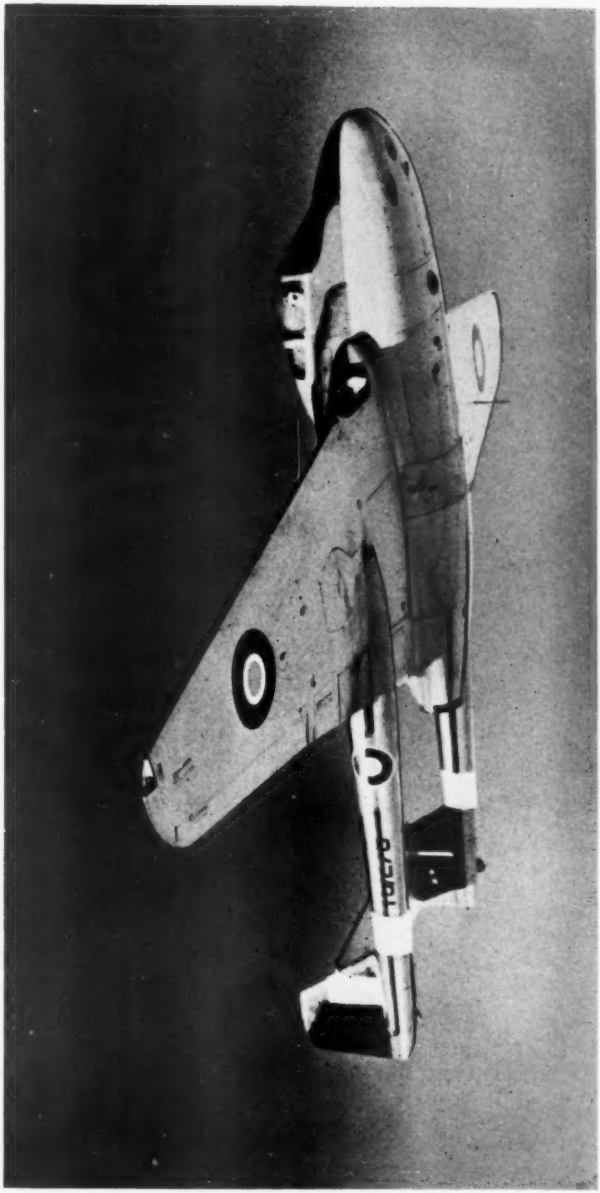


Fig. 19. Vampire single-seat fighter powered by Goblin II engine.

Fig. 20. Lockheed "Shooting Star." The prototype of this aircraft was equipped with a Goblin engine and was the first aeroplane to exceed 500 m.p.h.

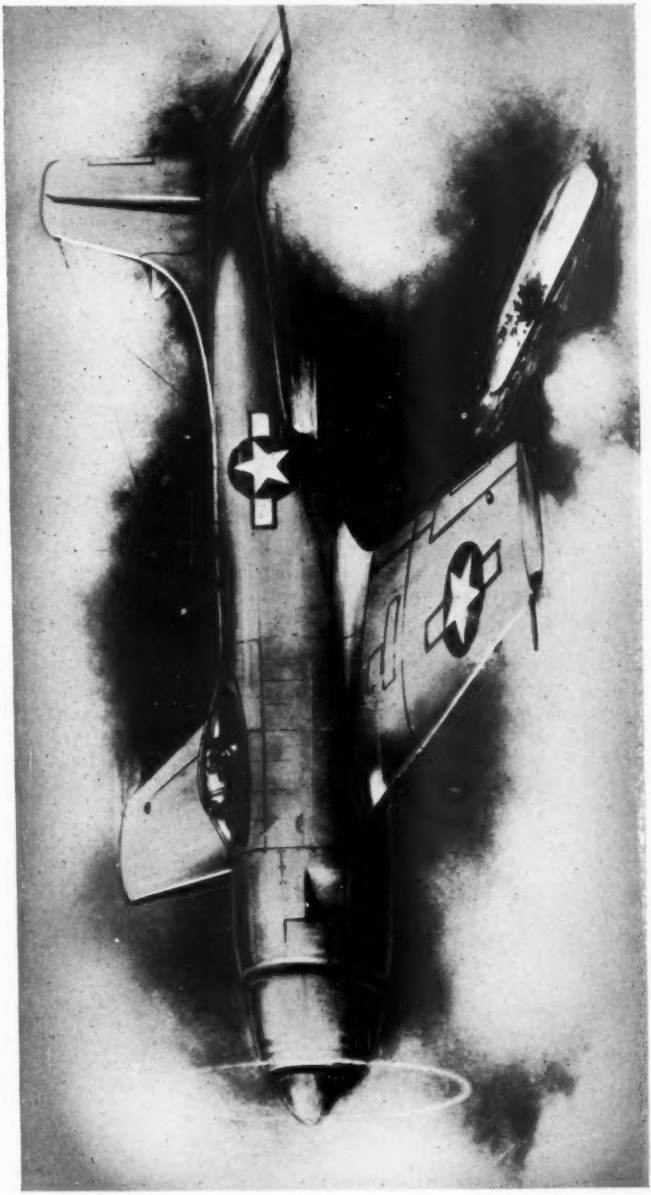


Fig. 21. Curtiss-Wright XF. 15.C. The Goblin engine in this machine was built by the Allis-Chalmers Company, and was used as an auxiliary, exhausting under the tail.

PROBLEMS RELATING TO THE PRODUCTION OF EXPERIMENTAL GAS TURBINE COMPONENTS

by R. MILLER. *

Presented to the Southern Section of the Institution, March 10th, 1948.

During last November Mr. Edwards, who is in charge of our Combustion Research Department had the privilege of reading you a paper dealing with the technical aspect of gas turbine development with particular reference to the D.H. Goblin and Ghost engines, and I have been asked to deal with the more practical side of the subject tonight.

However, before getting down to the business in hand I would like to confess that I cannot lay claim to that respected title of " Production Engineer."

As no doubt many of you know, it is usual for companies engaged on aero engine manufacture to have a strange custom of sorting out the more eccentric members of their staff and by forming them into an Engineering Division, they safely segregate them from their more normal Production brothers.

In addition to the usual requisites for design, development and research they are supplied with a varied selection of machine tools and equipment with which they are driven forward with great urgency to design and produce the prototype and development engines. The manufacturing methods used, if sometimes a little unorthodox, are very often extremely ingenious, but unfortunately they are generally more rudely referred to as " Knife and Fork." Being a member of such an Engineering Division I trust that you will make all the necessary allowances for my dealing with the subject mainly from this point of view.

DEVELOPMENT Mr. Edwards' lecture I think explained where we stand with the development of the Goblin and Ghost engines today. Manufacture of the first experimental Goblin was commenced in September 1941 and it ran for the first time in mid-April 1942. The output of Goblin production engines commenced during late 1944 and the current Goblin II having a maximum static thrust of 3,000 lb. went into production about a year later ; we hope to be producing further marks of Goblins with increase in the thrust in the fairly near future.

The Ghost engine, on the other hand, is not yet into production, although the Production Planning, Jig and Tool and Material

* *of The De Havilland Company.*

Supply Departments are busy at work to this end. Nevertheless, our experimental test bed and flight development programmes call for a surprisingly large number of prototype engines to be produced by the Engineering Division Shops. Up to date we have over twenty Ghosts engaged on our development programmes, with still almost as many again " on the stocks."

Although the Ghost provides a considerable increase in thrust, 5,000 lb. static, the design layout follows the Goblin sufficiently closely to allow me to deal mainly with the Goblin components during this talk.

The gas turbine engine includes many major components which are quite unlike those of its reciprocating predecessor, and they have brought their own peculiar problems to the Production Engineer. The compressor casings which are in magnesium alloy were, of course, rather larger than such components previously cast and machined by aero engine builders. Again, quite a high percentage of the components are of fabricated stainless sheet metal which has to withstand rapid temperature changes with maximums of up to 800° C. The design of these parts calls for accuracy to tolerances not previously asked for from sheet metal workers ; indeed, this type of engine has provided them with a new aspect of their craft demanding a high rate of skill and I would like to register here that they have done a very good job of work.

The necessity to produce some of the most important functional components by three-dimensional machining has provided ample scope for new ideas in this field and as it is quite impossible to deal with all the problems involved in the time at our disposal, I propose to deal with the two prime functional components only ; the compressor impellor and the turbine blade. Both of these have necessitated considerable thought and experimentation from the three-dimensional machining point of view.

THE COMPRESSOR IMPELLOR Figure 1 shows the first Goblin impellor to be produced ; alongside is a Gipsy Queen engine supercharger impellor which was, up to that time, the size of component we were used to producing. The Gipsy is 6.3 in. and the Goblin 31 in. diameter so you will gather that our Engineering Workshops had quickly to start thinking in a big way when the first drawings were issued in 1941. Before going on to describe how the Shops' staff attacked their new problem, I would like to pay tribute to our Design staff in having produced an initial design for such a component which has stood up to some years of development to increased power output, with only minor drawing changes having to be introduced.

Figure 2 provides a good idea of the shape in the seventeen vanes,

and it will be seen that the curvature required to give good smooth air flow through the compressor is considerable ; the extent of this is, of course, greater than in the double-sided impellors which had been used for gas turbines previously. However, as I think Mr. Edwards has explained, Major Halford adopted the single-side component for functional reasons which have been fully proved advantageous in practice. Firstly, it was chosen to take full advantage of ram effect in flight by using the most direct inlet ducting to the compressor, eliminating the eddying of air flow in the plenum chamber leading to the rear entry of the double-sided impellor. Secondly, the back diaphragm of the single-sided components is used as a balancing piston ; the compressor outlet pressure acting on this back surface balances the axial thrusts on the whole rotative assembly set up by the turbine, and the tendency for the impellor itself to screw the assembly forward into the air stream ; this provision relieves the front locating bearing of all thrust loadings other than what is necessary to prevent " shuttling."

Early study of the design showed that the extent of curvature excluded the possibility of machining the vanes straight and bending on forming bolsters, a method used for the production of some double-sided gas turbines, and supercharger impellors. It was, therefore, evident that we had to explore the best available methods of profile machining for our immediate requirements, and seek advice from the machine tool makers on the possibility of producing new special purpose equipment for the longer term production programme.

Before going on with the results of these investigations I would like to say a word about the supply of the necessary forgings. It will be appreciated that the physical properties of this rough material had to receive very special consideration in view of the high speed and consequent stresses to be accommodated. Die forging was, of course, specified not only to reduce to a minimum the superfluous material, but to provide the best possible conditions of grain flow. Figure 3 shows the Goblin forgings as supplied to us by High Duty Alloys weighing approximately 380 lb. ; they were originally called for in RR.59 but it was found necessary to increase the ductility and improve the uniformity of micro structure not only in each billet, but between billets. High Duty Alloys achieved this at the expense of a very small reduction in tensile strength, by reducing the silicon content to a maximum of .25% from .9% and arranging for the ingots to be produced by the continuous casting process. The new specification is RR.58.

PRODUCING VANE AND CAVITY SHAPES I will not occupy time with the more straightforward machining operations, such as turning, boring and drilling, but concentrate on the principal problem of

producing the vane and cavity shapes. Our investigations into the capabilities of existing types of profiling machines led us to choose the three-spindle B.L. Keller as being the quickest means of turning out our experimental batches of impellors. A special work and master carrying fixture had, of course, to be designed but no special alterations were made to the machine itself. An addition to the transverse travel of the work table, which is only $8\frac{1}{2}$ in., would have greatly speeded up the operations, saving cutter changes to deal with the maximum cavity depth of $12\frac{5}{8}$ in. but this was considered too major a change to make in the time available.

Two three-spindle B.L. Kellers were installed as quickly as possible, one for roughing, the other for finishing. The special fixtures and single cavity masters were identical for the two machines. Figure 4 shows three components being rough profiled. The forgings, having been previously turned and drilled for dowels, are mounted one above the other, the bottom component being dowelled to the fixture rotatable table, the other two in turn being concentrically and rotationally located to the first and each other by dowels in spacer plates fitted between the components.

Mounted above the work pieces are the single cavity master and its 17-pitch indexing plate. The master's base is located on the index plate by means of a removable dowel plug, and the whole set up, work, index plate and master, are concentrically located by a central arbor fixed to the rotatable table and located in a bridge structure at the top of the fixture. This arrangement allows the three components to be rotated to cut the various cavities, leaving the master in its correct relationship to the tracer.

When machining the experimental Goblin impellors by this method, it was necessary to make four cutter changes of varying lengths and diameters, from 1 in. to $\frac{5}{8}$ in. from periphery to hub due to the restricted table travel and narrowing down of the cavity at the hub. High speed butt-welded cutters were used with paraffin and lard oil coolant. The roughing of three Goblin components took approximately 120 hours.

The roughing operation left $\frac{1}{8}$ in. on all vane surfaces and as is still the practice today, heat treatment was carried out at this stage. The test pieces, which are taken from the entry and back bosses of the forgings, are, of course, heat treated with the components, and these must satisfy the following physical properties: minimum ultimate stress—24 tons/sq. in. and .1% Proof—16 tons/sq. in.; minimum elongation—6%. Brinell No. 116 to 130.

The finish profiling was carried out in two operations, semi-finish and finish. Figure 5 shows three components during these operations. The set-up is similar to that for roughing, but whereas the cutter worked in, across the cavity and out along the next vane

when roughing, the cutter works in and out on the one vane surface feeding upwards at each reversal during the finishing operations, the floor surface being tackled separately.

The three Goblin impellors took 125 hours for semi-finishing and 225 hours for finishing.

It will be noticed that the master cavity has an electrical contact wire around the outer edge of the vane shapes ; this is to provide protection against the tracer jumping the master, for if the tracer contacts this wiring the machine is immediately tripped. One or two tragedies taught us also the desirability of wiring up the master indexing plug to ensure that the machine could not be run if it was not in position to register correctly the work to master.

The machining of the first component proved that it was not desirable to cut the cavities in rotational sequence as this caused cavity floor sagging due to uneven stress relieving. The operation schedule was quickly changed calling for a diametral sequence.

I would record here that the B.L. Kellers, although taking perhaps rather a long time, did a very good job in the Engineering Division Shops producing some eighty Goblins before the Production Shops got going. We still use the same machines for the finishing of the Ghost impellor, but in this case, we are only able to deal with two impellors at a time, due to the increased component height.

So much for the utilisation of the general profiling machines which existed at that time, and as I mentioned earlier we had still to investigate the possibilities of what could be done to produce special purpose machines which would deal more rapidly with our production requirements.

SPECIAL PURPOSE MACHINES Messrs. Cincinnati wasted little time in getting down to the design of such a machine, working on their well known Hydrotel principle. Six of these machines have been built for us, five are installed in our Production Factory, the sixth being engaged in the roughing operations for the Ghost impellor in our Experimental Machine Shop.

Figure 6 shows a general view of the special Cincinnati machine. It will be seen that two components are machined simultaneously, these being mounted with their axes horizontal on the traverse carriage, along with a complete seventeen cavity master impellor. The two work components and this master are geared together so that they can rotate as well as traverse horizontally in unison. The machine head carries two independently-driven cutters as well as the main tracer which, of course, operates in the master impellor, the whole head having a horizontal movement parallel to the component axis ; the two cutters and the main tracer are fed down from the periphery to the hub of the impellors. It will be

seen that with rotation of the components and master, the horizontal movement of the head permitting the cutters to climb up and down over the vanes, and the down feed, the whole impellor surface is machined with a scroll cutter path, this being quite different to the B.L. method.

However, in describing only the three movements just mentioned I have presented the problem a little too simply. It will be realised that the curling form of the blade makes the continuous presentation of the cutter to the work at the correct angle to avoid interference a little tricky, particularly as the cutter rolls over the edge from the convex to the concave surface. This not only calls for a reversal of rotation but a rapid combination of this and horizontal traverse. Figure 7 shows how this combination of rotational and linear movement is achieved. A second tracer is mounted on the side of the machine head and this actuates on an off-set cam, of rather complex cylindrical shape, which is mounted on the back of the traverse carriage and geared to the components and master impellors but speeded up to 17/1, in other words, it completes one revolution for each circumferential cavity pitch. This off-set tracer dictates the horizontal traverse of the work and master in correct relationship to both the horizontal cutter and main tracer movement and the rotation of the work and master impellors.

There is one drawback in the Cincinnati machine, at least from the Experimental Engineer's point of view, which is that before you can start producing impellors of a given shape, you have first of all to produce a very accurate full master impellor to that shape, and after this master has been produced the off-set cam has to be made from it on the machine.

So here we find ourselves back again to the B.L. Keller for the making of the master and it will be appreciated that the Experimental Engineer's entire interest in a new impellor is focussed on getting it into an engine to prove it is functionally efficient at the earliest moment. So you will see that the faculty of being quickly adaptable to new design changes still makes the B.L. Keller method attractive to the Engineering Division. Needless to say, however, the Cincinnati type of machine is essential to the production man once the design is proved to be satisfactory and, of course, at this stage it is a great aid also to the Experimental Engineer, to produce rapidly the quantity of components he requires to equip his development engines.

SOME PRACTICAL PROBLEMS As must be expected with the introduction of such new and complex machines, some troubles were experienced. They were principally as follows : the cutter heads were initially designed to run at 8,000 and 10,000 r.p.m. for roughing and finishing respectively. These high speeds, coupled with the

rather heavy cuts required particularly during roughing, produced rapid wear in the cutter spindle roller bearings. Also it was found that the need for extreme accuracy in the rotation gearing between master and component impellors and the off-set cam had not been fully appreciated, and in addition we had not been sufficiently accurate when producing our early master impellors ; this, of course, was no fault of the machine itself. Steps were quickly taken to overcome these difficulties. The reduction of cutter speed naturally required the most work to correct. It was found necessary to reduce the speed on roughing from 8,000 to 3,000 r.p.m., and at the same time increase the proportions of the spindle bearings. To do this the whole head had to be altered, incorporating belt drives between the driving motors and cutter spindles. In the case of the finishing operations it was not necessary to alter the direct cutter drive but the speed was reduced to 8,500 and the bearings strengthened as in the roughing machines.

Some of this modification work has still to be carried out on one or two of our machines but the impellors are now being produced in three operations, roughing, semi-finishing and finishing, each taking 20 hours per two components. High speed steel cutters with two spiral flutes are used for roughing, while semi-finishing and finishing is carried out with " Teco " tip single tooth cutters. The coolant used in all of these machines is soluble oil copiously applied from multi-jets mounted around the cutter collets.

This big reduction in production time for profiling was not achieved in silence ; the resonant nature of the work coupled with the high cutter speeds resulted in considerable noise and a battery of these all going together necessitated the construction of an acoustically-treated house in our Production Factory.

During the period when the Cincinnati " Wizard " was being developed, Allis-Chalmers of Milwaukee had been instructed by the U.S. Government to undertake the production of the Goblin for the American War effort, and they were naturally also interested in devising methods of quick impellor manufacture. As a result the Keller people were asked to investigate the possibility of improving the existing B.L. method, and after collaboration with Allis-Chalmers and ourselves acting as advisers, a design was produced which was based on their B.G.1 machine.

This arrangement attacked the problem from yet another angle. Figure 8 shows a general view of the machine ; the principal alterations from a standard B.G.1 are the additions of a special work and master fixture the motivation of which is linked up with the main machine movements, and the provision of four tracers. It will be seen that only one component is dealt with at a time ; this is mounted with its axis vertical. The vane surfaces are machined with a taper cutter which by tilting and rotating the

work and at the same time moving the cutter in three planes line-cuts the vane surface by rolling down from entry edge to cavity floor. It is not possible to show all the various masters, templates and tracers by photograph, but perhaps the diagrammatic sketch shown in Figure 9 will explain the position and function of these. Basically the fixture has two platforms one above the other, both of these platforms being linked together so that they can tilt in unison ; the bottom platform carries the work piece on a rotatable table, while the top platform carries two solid masters, one representing the concave and convex vane root radii, set up concentrically with the work and rotatable with it. The other, which represents the cavity floor surface, is mounted to the side of the root master and although tilting with the work it does not rotate. The two tracers operating on these masters are attached to the cutter head.

In addition we have two templates fixed to the main machine head at right angles to each other, one template dictating the fixture tilt, the other the machine head off-set. Two tracers attached to the fixture actuate on these templates. The procedure of profiling with this machine is to complete, say, all the concave vane surface first by indexing each vane into position, following up with the convex surfaces in a similar manner. It should be explained here that there is a separate pair of off-set and tilt templates for the concave and convex surfaces ; these have to be changed over on the machine. It is also necessary to reset the root master in relationship to the work to engage its tracer in the appropriate track when changing over from one surface to the other.

The two solid root and floor masters are made from castings machined to drawing, but the template shapes are worked out on the machine itself. To do this we have to produce an accurate model representing a concave and convex shape somewhat similar to that used on the B.L. Keller. This model is substituted for the work on the fixture and a conical dummy bar ground to the dimensions of the cutter to be used is fitted to the collet. The dummy cutter is presented to the blade shapes on this master working down in set increments from the entry to the cavity floor ; the fixture is tilted and the machine head off-set at each step to bring the cutter into accurate line contact with the model surface. The resultant ordinates obtained from these settings are recorded on soft sheet templates, the shape being ultimately transferred to the two working templates. Final corrections must be made to the working templates by taking trial cuts on sample blades ; this is necessary to accommodate tool and component vane deflections, etc.

Four of these machines were obtained by us, two being used to finish the Ghost impellor in our Experimental Shops in the first instance. They were later transferred to the Production Factory to assist with Goblin impellor output while the Cincinnati's were

being modified. They now work in parallel with the Cincinnati's for semi-finishing and finishing of the vane surfaces only, B.L. Kellers' being used to deal with the cavity floors as this operation can be done much quicker with the three-at-a-time set-up.

In summing up the three profiling methods described, we see that there is an inverse relationship of adaptability and operational times between the machines.

The B.L. Keller being the quickest to modify with only one single cavity master to alter takes much the longer operational time, that is, approximately 157 hours per Goblin component for roughing and finishing. The B.G.1 adaptation takes longer as for the maximum change we would require two new top masters and four templates, in addition to the single cavity model for the making of the new templates. In this case, however, we have reduced the time for roughing and finishing to approximately 80 hours.

The Cincinnati obviously takes the longest to adapt as it means making a new single cavity master, followed by the making of a complete master impellor on the B.L. This has to be hand-finished to considerable accuracy and when it is completed we still have the lengthy job of producing the off-set cam. Nevertheless the operational time of 30 hours per component pays a large dividend to the Production Engineer.

FINISHING AND INSPECTION

I will just say a word on the hand-finishing and inspection before leaving the impellor. When the component is passed over for hand-finishing there is some +.050/.060 in. left on the vanes and the first operation is to remove all machine "stepping," clean up the root radii and form the entry nose radius, using acorn rotary files. This is followed up by using a belt-driven emery bob specially designed to facilitate getting right into the cavity roots, using grits of from 60 to 120. In the early days this was followed by high finish polishing with much finer grits, but we now subject all impellors to vapour blasting process in three 35-minute stages and when this has been completed the component is anodised.

During hand-finishing the component is subjected to inspection at scheduled stages. Figure 10 shows how this is carried out by fitting a suitably shaped sheet metal mask on to the vane surface. This mask has holes at specially selected stations of known sectional vane thickness and 10/1 magnification clock reading calipers are used to obtain the thickness at each station. The readings are logged down on a chart and used by the scurfer while carrying out the next stage. The vane thickness tolerance allowed on the finished component is —.010/+.030 in., but the question of balance has also to be considered, and it will be appreciated that it would be possible in a component of this width to be in static

balance but out in dynamic balance, due to couples. Check dynamic balancing is, therefore, carried out during the hand-finishing operations and the scurfer is guided in to remove vane thickness within the tolerance to improve the balance.

While on the subject of inspection you will realise that the caliper gauging just mentioned would not check vane shape. Figure 11 shows a fixture which has been produced for this purpose. It will be seen that the component is located on a rotatable and indexing table mounted above a master which is built up of steps each having two slots, these being accurately placed to represent the concave and convex surfaces of an accurate blade form. The bottom ball of the double " stilo " is located into these stepped slots in turn, the top ball is free to move in all planes and actuates a gauging clock. Comparative plus or minus readings are, therefore, obtained for set station positions; the comparisons of these on a chart will show any malformation of the vane surface over its area. Every impellor is not put on this fixture but checks from the profiling machine are periodically carried out on it.

TURBINE ROTOR BLADES Turning now to the next important component, the turbine blade, it might be thought that considering the great number of steam turbines which have been built since early in the century, the blade design and manufacture would not have presented any very serious new problems, but I am afraid that was not so. The reasons are not very difficult to explain : firstly, the gas turbine working temperature is 700/800° C., whereas the steam turbine operates at about the same ° F. and secondly, the operational speeds are in general much higher. Both of these conditions have called for very considerable research by the metallurgist to produce new qualities of heat resisting alloy steels with particular attention to creep characteristics. Again the aerodynamic shapes demanded are more complex, and the accuracy and finish required are more exacting.

The early Goblin engines had one hundred and thirteen blades, the chordal width being 1". These performed very well against design requirements, and mechanical failure was practically nil. However, the designers considered that it would be wise to increase the component strength and a new design was issued increasing the chordal width by a third. This reduced the number of blades per engine to 83 and the stress at full load from 16 to 8½ tons/sq. in. The performance was identical to that with the original type. This new design was standardised and is the blade used in the current Goblin production engine. I should say here, however, that the Experimental Shops have produced various versions of

both the narrow and wide chord types during the past six years and, as will be explained later, a new form will shortly be going into production.

We have always used drop forgings in the making of our blades. In 1941 these were produced in Rex 78 and Stayblade material with a recommended maximum working temperature of around 650° C., and as you will realise the metallurgists have since then been carrying out unceasing research in an effort to provide materials which will allow the designers to increase the engine efficiency by using higher working temperatures. It is a hard battle and advances are not easily gained in this direction ; however, we are now using Nimonic materials which permit us to go up to 750/800° C. Figure 12 shows the forging and the various manufacturing operations up to the finished component. It will be seen that the forging has a club at each end, the bottom club being machined to form the fixation root and the top club providing good holding and locating datums, and being removed prior to the polishing stages. The first operation is to machine the two clubs to close tolerance as a rectangular bar ; this provides good locational datums in three planes.

PRODUCTION OF BLADE SURFACES

It will be appreciated that the producing of the blade surfaces is the real problem and I will not occupy time in dealing with the more straightforward operations.

The designs of the narrow chord and current production wide chord blades called for an irregular shape on the back or convex surface. The concave surface, however, was a simpler proposition in that its cross sectional outline was formed by a single radius, the disposition to the blade axes of which varied evenly in ratio to blade length. I will treat the two surfaces separately, dealing in the first instance with the methods used in the Experimental Shops.

Figure 13 shows the convex surface geometry of the early narrow chord blade. Sections at the blade tip, root and mid-length only are given and it will be seen that each profile comprises two tangent radii, the dimensions of which are constant throughout the blade length but their disposition in relationship to blade length varies irregularly. Three-dimensional forming was, therefore, called for, and in the early days it was generally accepted that the next method was to form grind. The diagram shows the type of fixture we used in the Experimental Shops. This took the form of a mandrel, on which a three-dimensional cam was co-axially mounted with the work. The mandrel was centred between two swinging arms and driven through a " live " centre. The fixture was designed to work on a Cincinnati universal grinder, a special follower and bracket being fixed to the machine bed.

Fourteen-inch wheels dressed to a .10 in. radius provided the

necessary line cut. Using a 13 in. diameter follower it was possible to dress the wheel down to 12 in. diameter before the translating tangent errors amounted to .001 in. However, the heat-resisting material of the components made short work of the wheels and it was only possible to finish 80 blades per wheel ; roughing cuts could, of course, be carried out with wheels under 12 in. diameter. Nevertheless this method served very well its purpose of producing experimental batches of blade, providing reasonable finish and accuracy.

When the wide chord blade design was issued thoughts were directed to form turning and a fixture was designed using a negative cam to provide good positive cutting action. Figure 14 shows this arrangement in diagram. As in the grinding fixture the three-dimensional cam (but in this case negative) is mounted co-axially with the work on a mandrel which is supported on two pedestal bearings fixed to the lathe bed. The fixture base is arranged to slide along the bed and is connected by a bar to the normal machine saddle. A slide carrying the follower and cutting tool is mounted on the fixture base and is capable of movement dictated by the cam normal to the mandrel axis, a spring being fitted to keep the follower applied to the cam.

This arrangement gave very satisfactory results and is the method used today in our Experimental Shops to produce the latest type of both Goblin and Ghost blades. Female operators do the job and each machine is fitted with two fixtures arranged in tandem. The drive to the second is transmitted through the first, the two blades being disposed at 90° to each other to disperse the cutting load. Figure 15 shows the fixtures mounted on a Bradford lathe.

Turning to the concave surface, Figure 16 shows the geometry of the shape in the narrow chord blade and it will be seen that the centre of the forming radius moves evenly round a fixed centre in relation to blade length. It was, therefore, possible to produce the surface by line cut milling, rotating the work round the fixed centre shown on the diagram as the cutter is fed in. A sectional sketch of the fixture used for this purpose is shown in the diagram. The work is mounted co-axially on the fixed centre with a sleeve incorporating a helix cam track designed to provide the correct pitch. A spring loaded plunger pushing on the machine head carries a follower which operates in the helix track to position the work in correct relation to the cutter.

This type of fixture is used for the manufacture of the wide chord Goblin blade at present in production. The latest development Goblin blade, however, has an irregular concave surface formed by two tangent radii in similar fashion to the convex surface.

This new requirement has made the manufacture more difficult,

it being no longer possible to mill. The Experimental Shops have produced a form turning fixture on similar lines to that used for the convex surface. A negative cam is again used but it is not possible to duplicate this fixture on one machine. It is not quite such a simple proposition but nevertheless it has worked well in producing our experimental batches.

CAM MANUFACTURE The making of the cams for the form turning fixtures presents an interesting problem, more particularly as you will realise that the adaptability of the method to accommodate design changes depends on the speed and accuracy with which these can be produced. Time will not allow me to go fully into this, but I will try to cover it briefly. In the design of the cam it is important to choose carefully the rotational centre if tangent errors in the case of form grinding and changes in cutting tool rake in the case of turning are to be avoided.

In the case of the form grinding fixture a master cam was produced by building it up of discs, the ends of which had been shaped to suit the blade section at these stations. Figure 17 shows a diagram of this arrangement. The discs were mounted on a mandrel, being accurately located to each other in the polar sense, and the whole cam was blended off by hand in the tool room and carefully checked by metrology.

As it was not possible to use this built-up cam for component grinding due to the constant follower wear rounding off the disc edges, the shape was transferred to a solid cast steel working cam on the grinding fixture itself.

The negative cams for form turning took a little more thought. Due to the necessity of using a roller follower and a point cutting tool, it will be seen that the cam shape had little resemblance to blade shape even in its negative sense. We had, therefore, to produce a positive cam as in the case of form grinding, and mount this in the normal component position on the form turning fixture, the material for the negative cam being fitted to the mandrel in its normal position. A hardened point follower replaced the component cutting tool, and the roller follower and its bracket were replaced by a cutting tool. With this set-up the negative cam was rough-turned to the approximate shape. After hardening the cam was again set up, but this time a tool post grinder with a wheel of diameter equal to the roller follower to be used replaced the cutting tool, and the cam was finish ground to the correct shape. The production of the working negative cam on the fixture is of great value as any translating errors in the fixture itself are cancelled out. We are now developing speedier methods of producing these cams.

I will now turn to the methods used by our Production Shops for these operations on the present production design of blade.

In exploring the convex surface, the Planning Engineers found that by going forward to Design for a small concession in shape, they were able to produce the surface in three Servo milling operations.

For the first two operations the blades are set up in fixtures set at a small angle across the table (Fig. 18) and a form ground barrel cutter is rolled over the surface, the raising and lowering of the machine head being, of course, dictated by the usual Servo mill cam. Roughing and finishing operations are carried out with this set-up. Due to the fixture angle producing a cut which is not at right angles to the blade axis, the third operation is necessary, which is to cut the blade station adjacent to the root platform and form the fillet radius. Again a Servo mill is used with a narrow radius formed cutter, the fixture this time being presented parallel to the cutter arbor; a small step is left where the two cuts meet, and this is blended during polishing. It will be noted that double fixtures are used in these operations, to provide pre-loading.

The concave surface is produced by methods similar to those used in the Experimental Shops previously described but double fixtures are used as shown on Figure 19. Pre-loading work carriers have also been incorporated to speed up the operation.

As I have already mentioned, a new design of blade has recently been tried out in the Experimental Shops and it will be going into production in the next few months. Our Production Engineers have found it necessary completely to change their methods of blade forming to accommodate this new design. Firstly, it is no longer possible to Servo mill the convex surface and an adaptation of the negative form turning idea has been incorporated into "Maxicut" lathes, Figure 20. The back tool box carries two cutting tools which come in and form the tip and root stations only; this is automatically followed up by the main side cutting tool coming in from the front, picking up in the track of the tip station tool and feeding along until it blends into the root station already cut.

As already stated the concave surface is now of irregular shape involving two tangent radii, and it is proposed to carry this out by a shaping operation using a special adaptation of the Drummond gear shaper, Figure 21. The blade surface is produced in a series of shaping cuts along the blade length, the feed being obtained by slowly rotating the head system from leading to trailing edge of the blade. The required shape is dictated by a three-dimensional cam.

I am unable to give you any opinions on these matters as the machines are just being installed in our Production Factory.

INSPECTION METHODS Before leaving the machining of the blade surface I would like to say a brief word on inspection methods. In the early days we worked with shutter type gauges applied to the various blade stations, but we found these to be very unsatisfactory as they did not provide a very accurate method of finding out the magnitude nor the nature of the errors and they were also slow and cumbersome.

Figure 22 shows the type of checking fixture used. This fixture operates basically in the same manner as the machining fixture, only in this case the cam is formed by a series of two-dimensional plates representing stations, and for simplicity of manufacture and checking accuracy they are positive in shape and twice full size. The motion is transmitted to the reading clock through a reversing and 2 to 1 reducing leverage. The clock is set to zero by means of a setting piece before the component is fitted into the fixture and if the blade is 100% accurate all over the surface, the clock will read zero when the mandrel is rotated from leading to trailing edge at each station.

It will be seen that the plus and minus readings not only provide a quick evaluation of the extent of any errors but a ready analysis of their nature, that is, general thickness up or down, contour shape wrong, or errors in twist over the length of the blade.

CONCLUSION From the foregoing résumé of the methods applied to the production of the three-dimensional shapes it will be apparent that there are many ways of achieving the same object, and I am quite sure that we have by no means exhausted the potential of brainwaves to deal with these interesting problems. I would, however, draw attention to the two viewpoints which must be considered in this connection. Firstly, the Experimental Machine Shop Engineer must continually watch the adaptability of any method he employs, as the success of engine development naturally depends on how quickly various design versions of the components can be made and tried on the test bed. The Production Engineer's first interest, on the other hand, must be to produce the component with quick repetition after the design has been stabilised ; adaptability cannot obviously be completely ignored but it is secondary.

It is not my wish to be too critical of our Machine Tool industry but I have felt that they could have helped the engine manufacturer a little more on the production of compressor, turbine and stator blading. We seem to have been left, to a great extent, to our own devices in this field. It may be that this can be explained to some extent, at least during recent years, by the amount of research being carried out on precision casting of such components,

and frankly I feel that there is a considerable future for this method when the laboratory stage of development is fully completed and the costs become more competitive in this country. This naturally applies particularly to engines incorporating axial type compressors.

During this talk I have tried to speak not only from the Experimental Engineer's view, but to give some information about our Production Shop methods and although as I explained at the beginning I do not feel completely competent to deal with the latter subject, I trust that it has proved of interest.

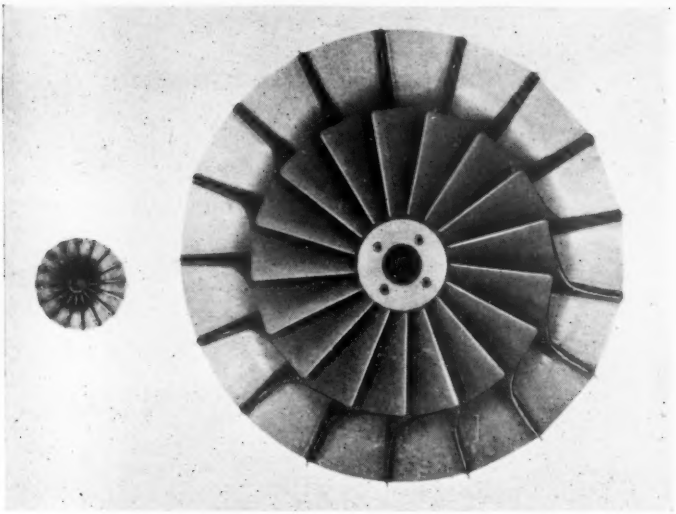


Fig. 1. The first Goblin impellor to be produced (right), shown with a Gipsy Queen supercharger impellor.

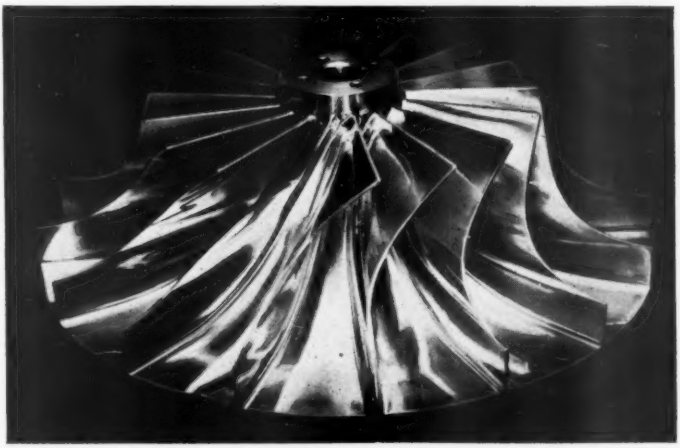


Fig. 2. Goblin impellor showing the considerable vane curvature required.

Fig. 3 Goblin impellor forgings before machining.

Fig. 4. Three components in the process of rough profiling.

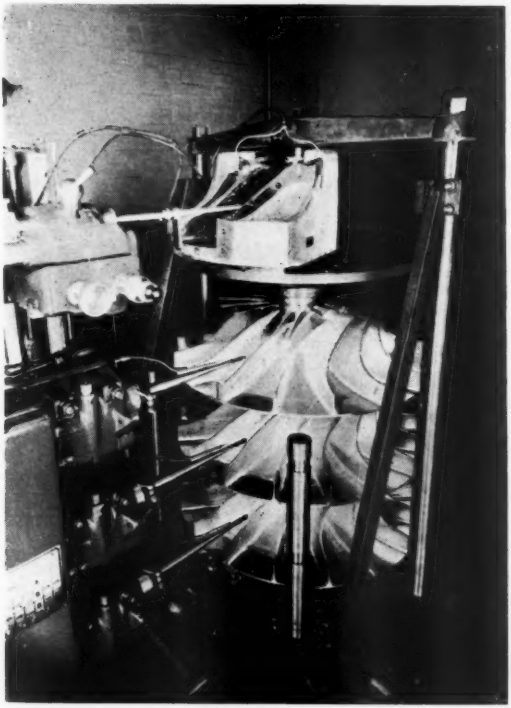


Fig. 5. Three components in the process of finish profiling.

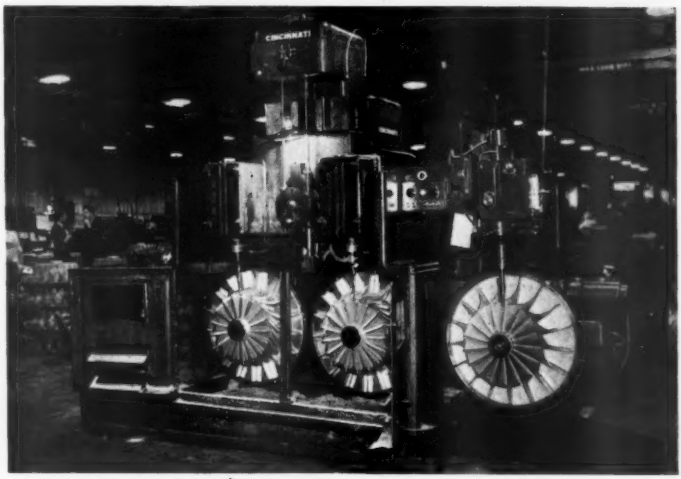


Fig. 6. General view of the special Cincinnati machine.

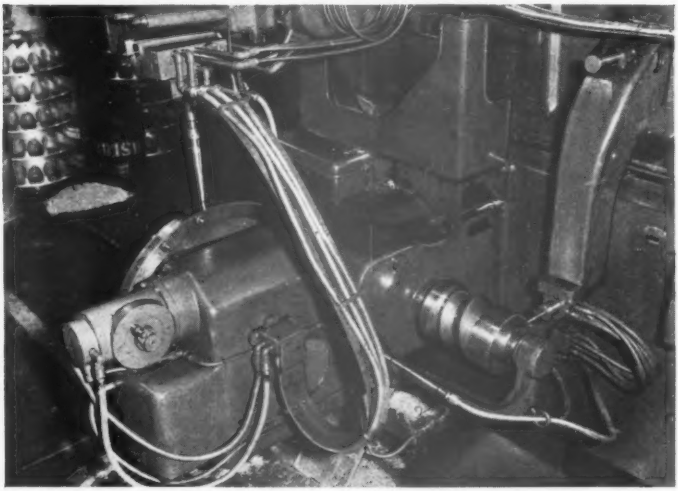


Fig. 7. Showing how the combination of rotational and linear movement in impellor machining was achieved.

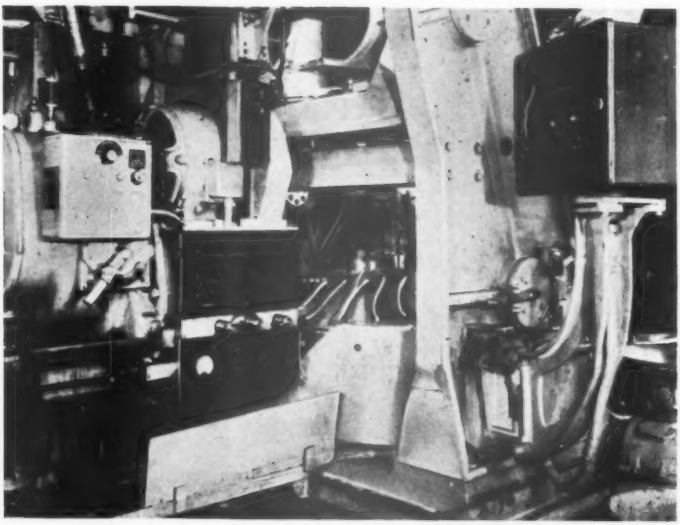


Fig. 8. General view of machine based on the Keller B.G.1.

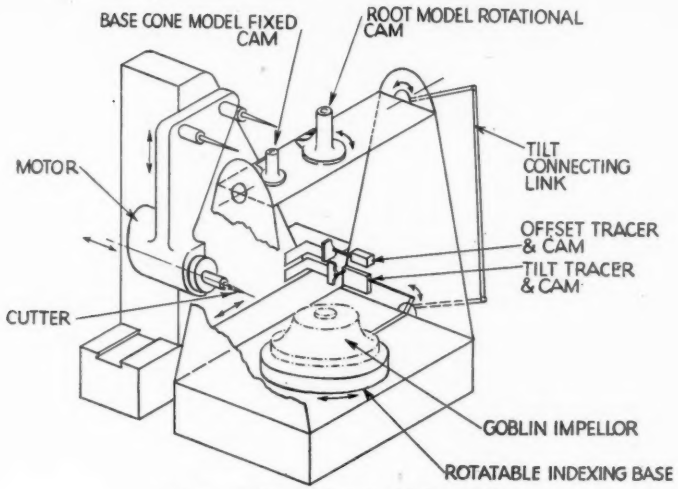


Fig. 9. Schematic layout of B.G.1. Keller.

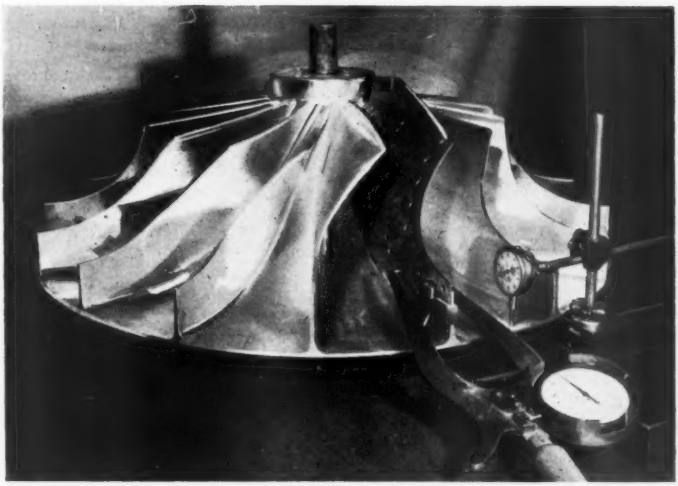


Fig. 10. Inspection of vane thickness.

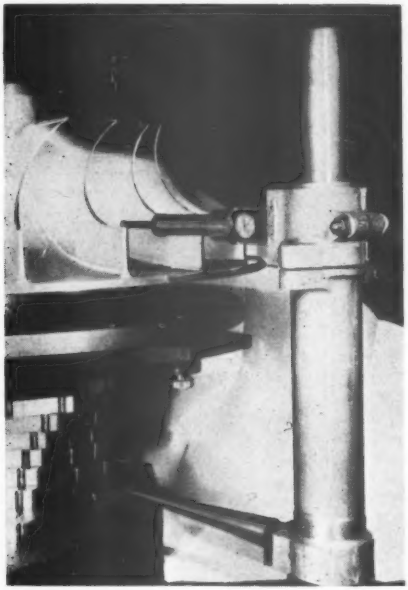


Fig 11. Inspection of vane shape.

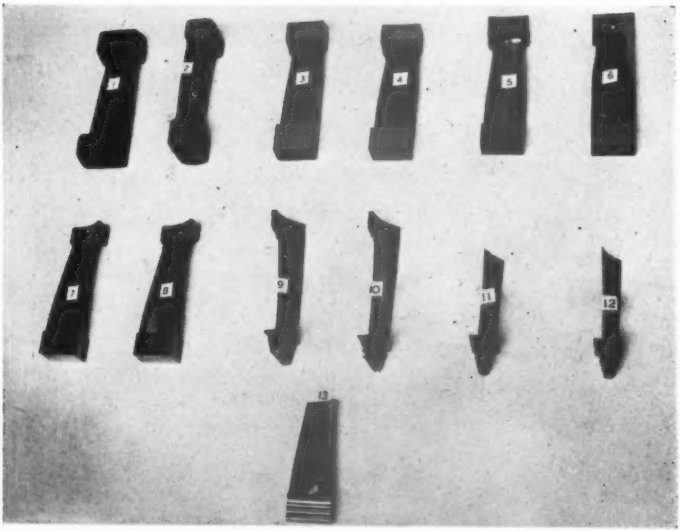
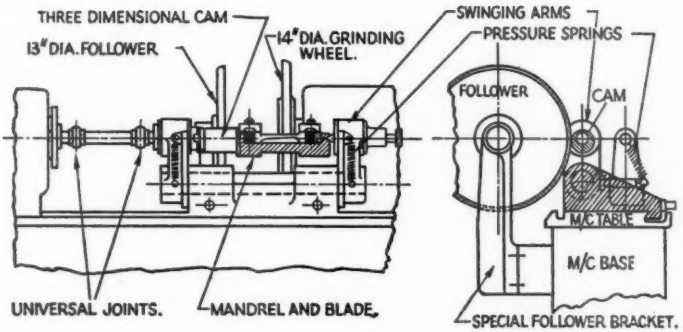


Fig. 12 Turbine rotor blades—forging and various manufacturing operations up to the finished component.



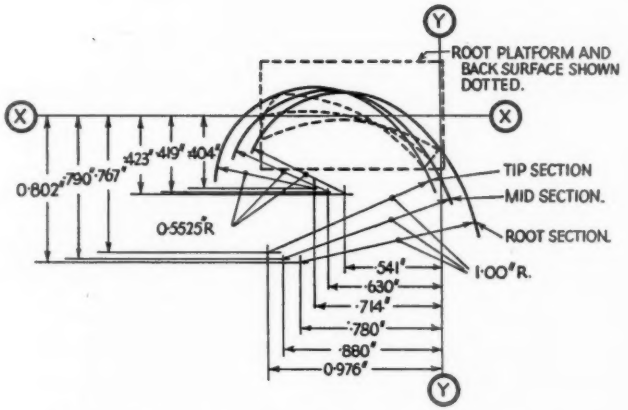
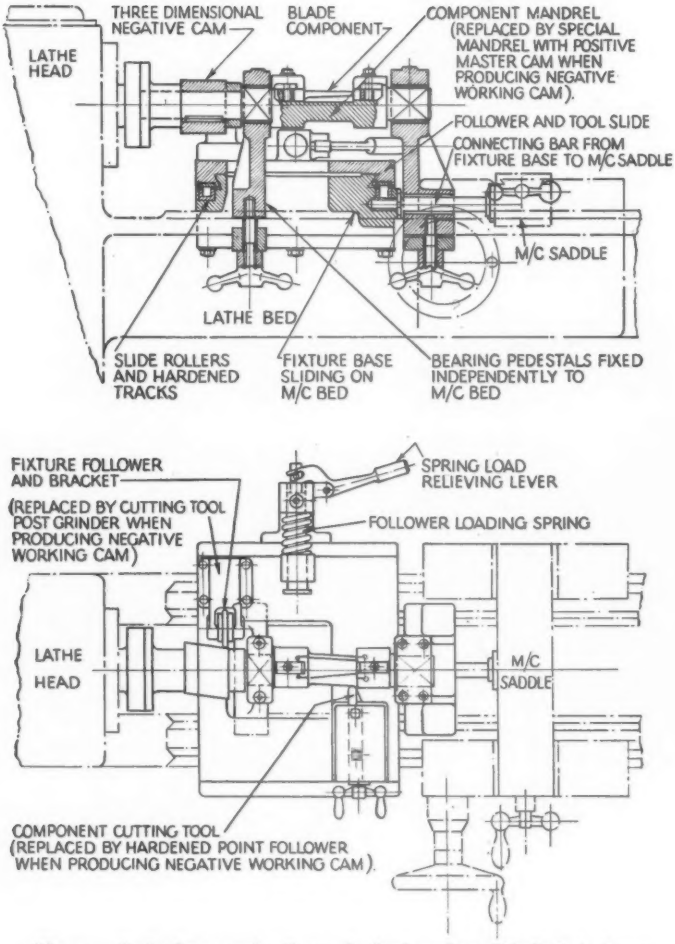


Fig. 13. Back surface grinding machine (*top*) and convex surface geometry of the early narrow chord blade (*bottom*).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COMPONENT MANDREL (REPLACED BY SPECIAL MANDREL WITH POSITIVE MASTER CAM WHEN PRODUCING NEGATIVE WORKING CAM).
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FOLLOWER AND TOOL SLIDE
CONNECTING BAR FROM FIXTURE BASE TO M/C SADDLE
M/C SADDLE
LATHE BED
SLIDE ROLLERS AND HARDENED TRACKS
FIXTURE BASE SLIDING ON M/C BED
BEARING PEDESTALS FIXED INDEPENDENTLY TO M/C BED
FIXTURE FOLLOWER AND BRACKET
(REPLACED BY CUTTING TOOL POST GRINDER WHEN PRODUCING NEGATIVE WORKING CAM)
SPRING LOAD RELIEVING LEVER
FOLLOWER LOADING SPRING
LATHE HEAD
M/C SADDLE
COMPONENT CUTTING TOOL (REPLACED BY HARDENED POINT FOLLOWER WHEN PRODUCING NEGATIVE WORKING CAM).

Fig. 14. Lathe form turning fixture for back surface of blade (m/c shown chain dotted).

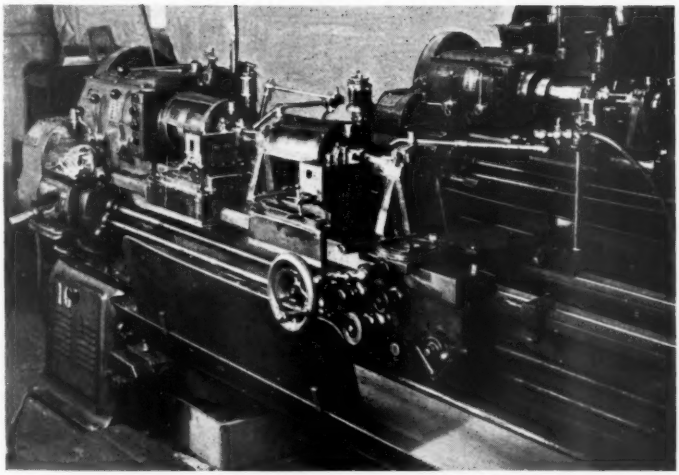

Fig. 15. Fixtures, as shown in Fig. 14., mounted on a Bradford lathe.

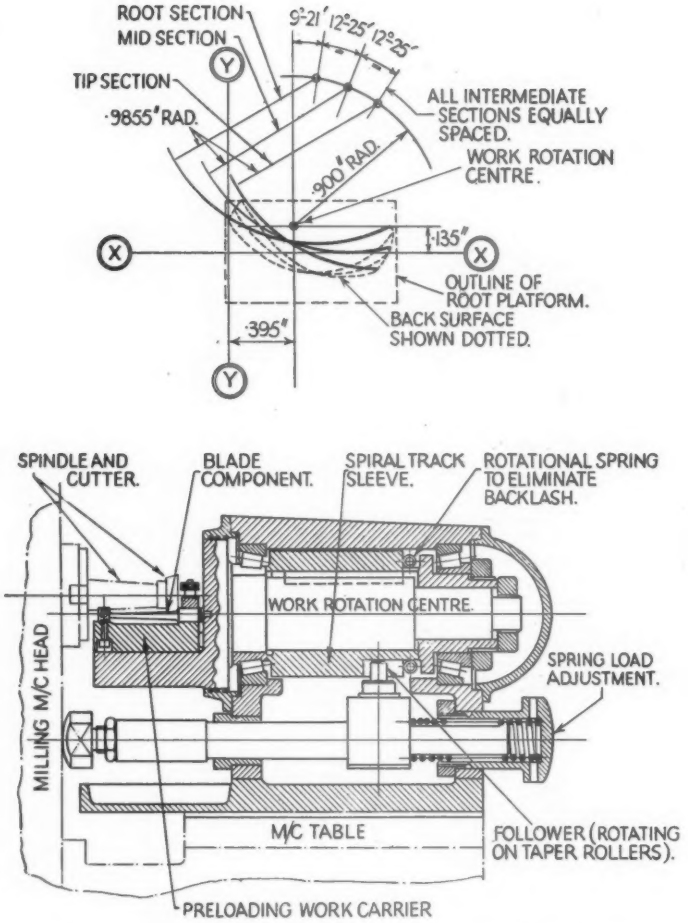

Fig. 16. Concave surface geometry of narrow chord blade (*top*) and inside surface milling fixture (*bottom*).

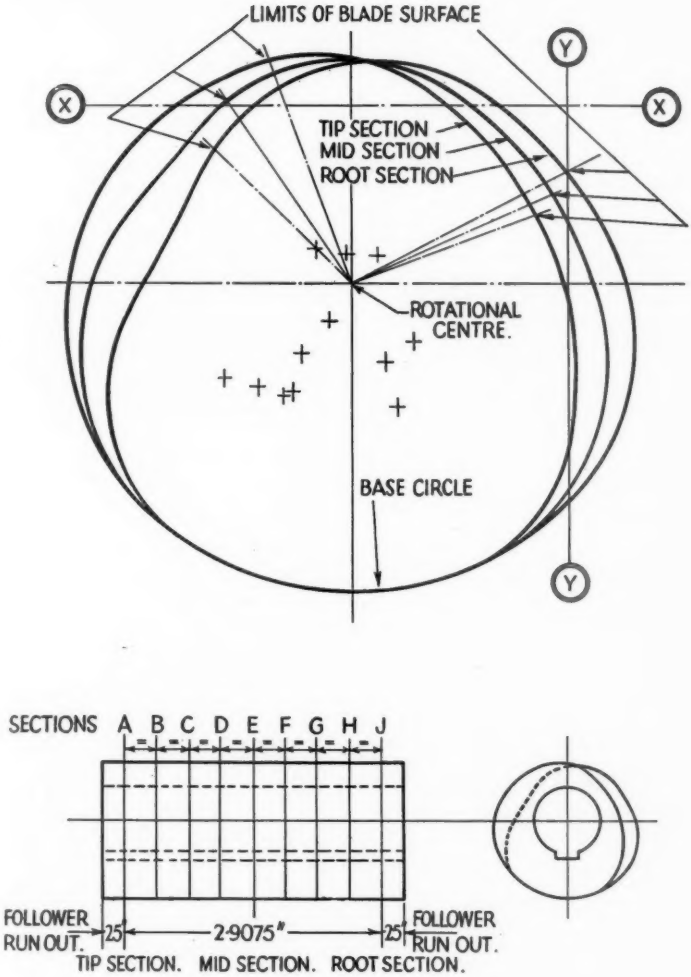

Fig. 17. Master Cam for form grinding fixture.

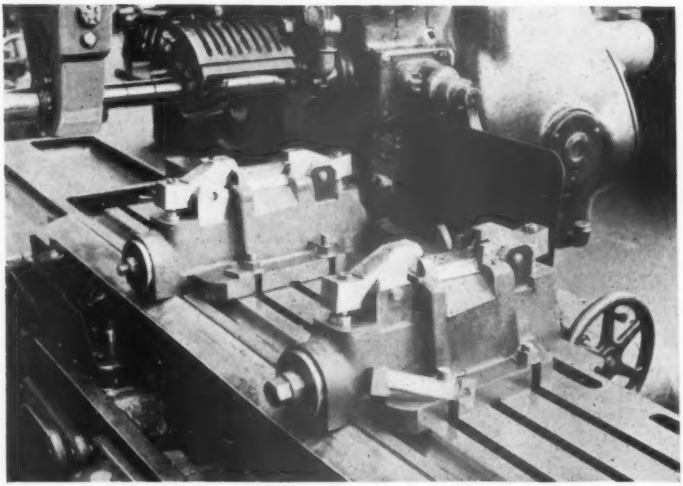

Fig. 18. Fixtures used in producing convex blade surfaces.

Fig. 19. Fixtures used in producing concave blade surfaces.

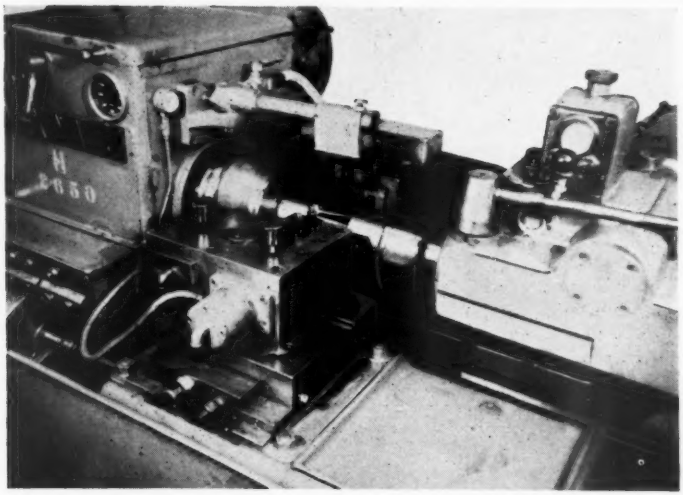

Fig. 20. "Maxicut" lathe.

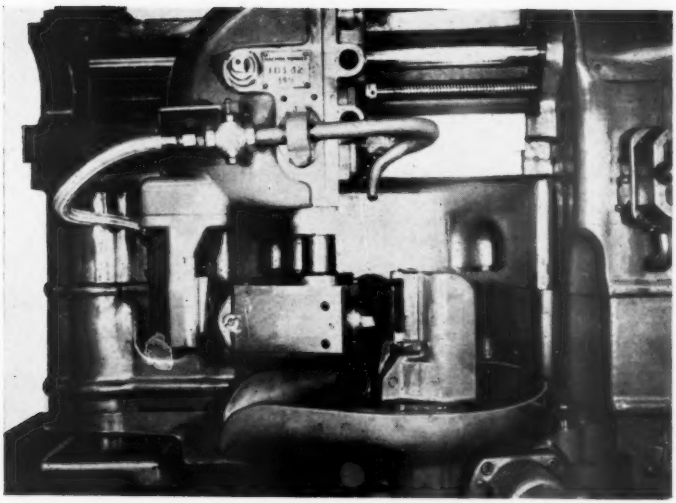

Fig. 21. Special adaptation of the Drummond Gear Shaper

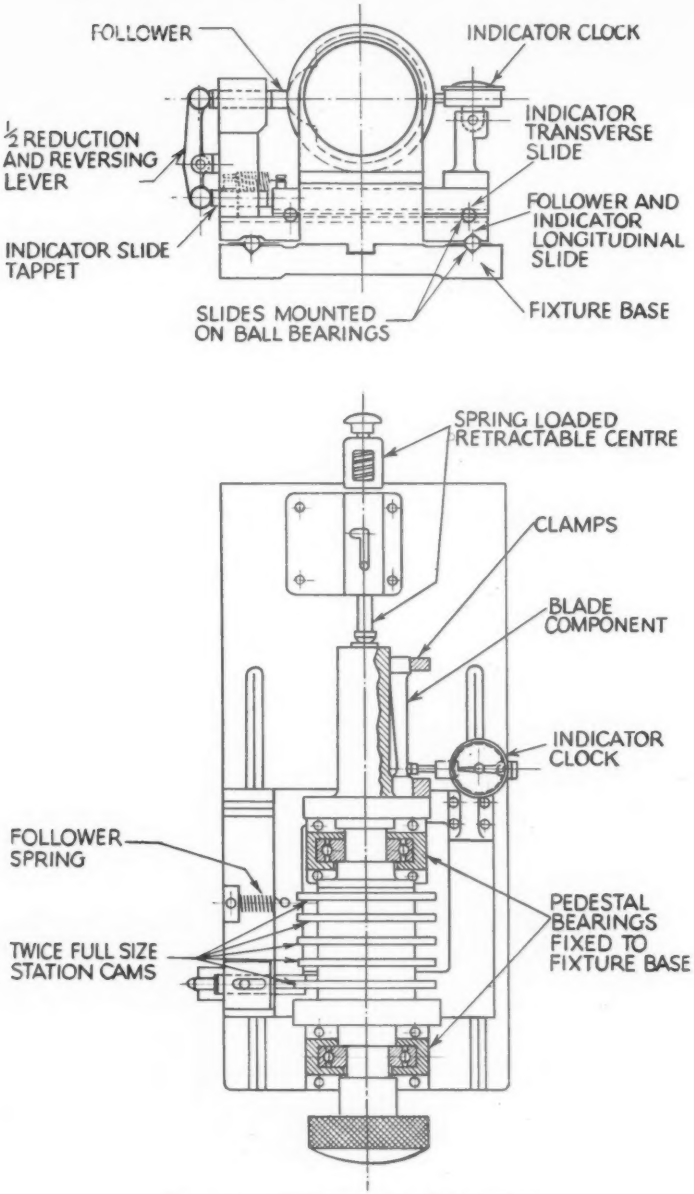

Fig. 22. Inspection Fixture for blade surface.

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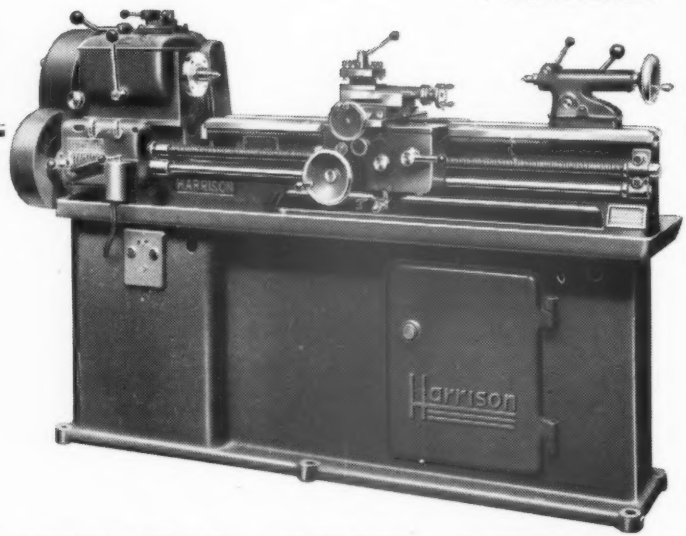

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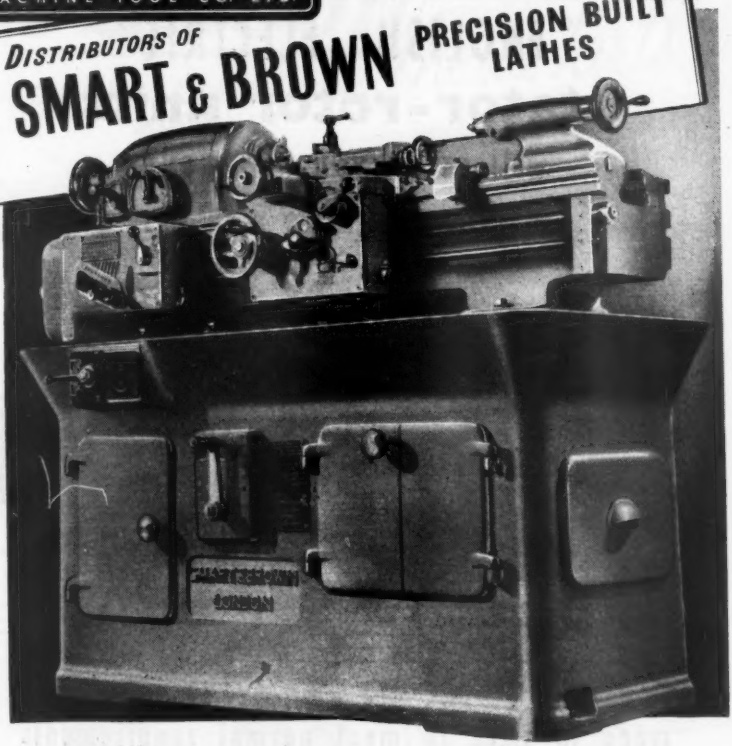

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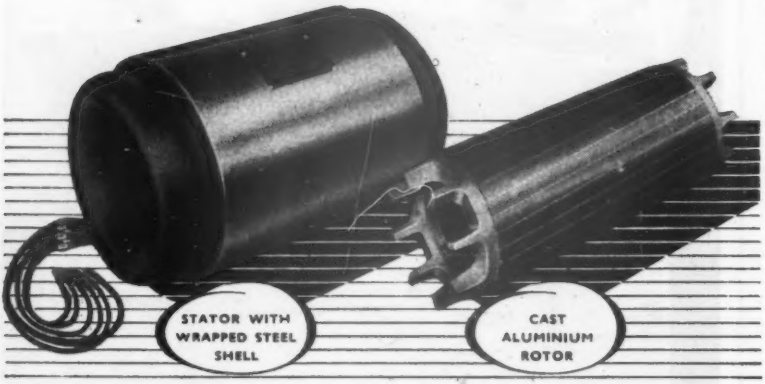

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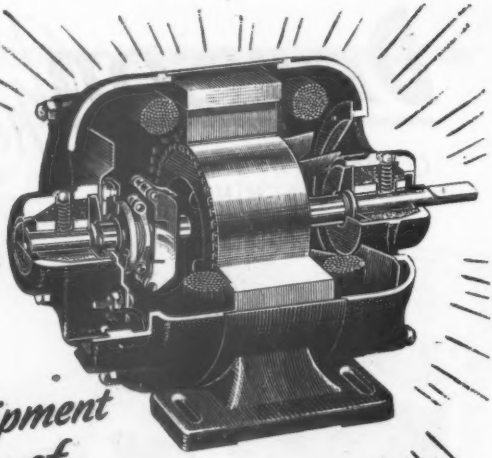

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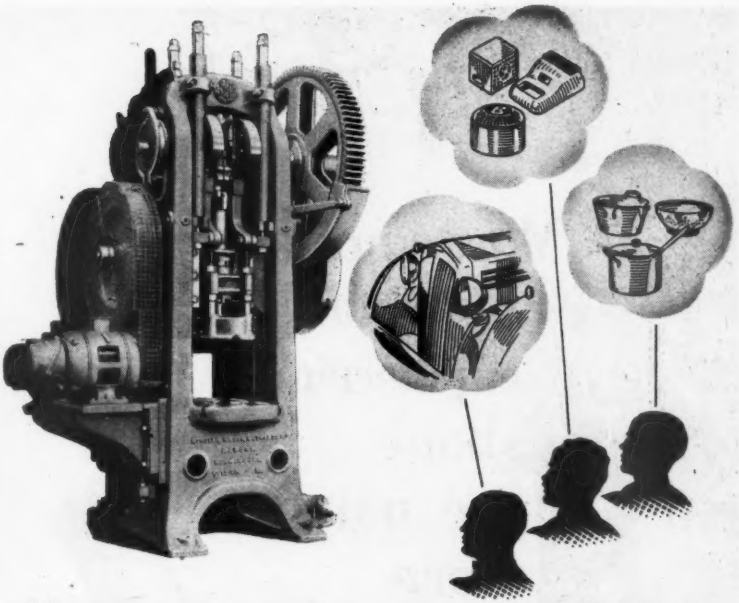

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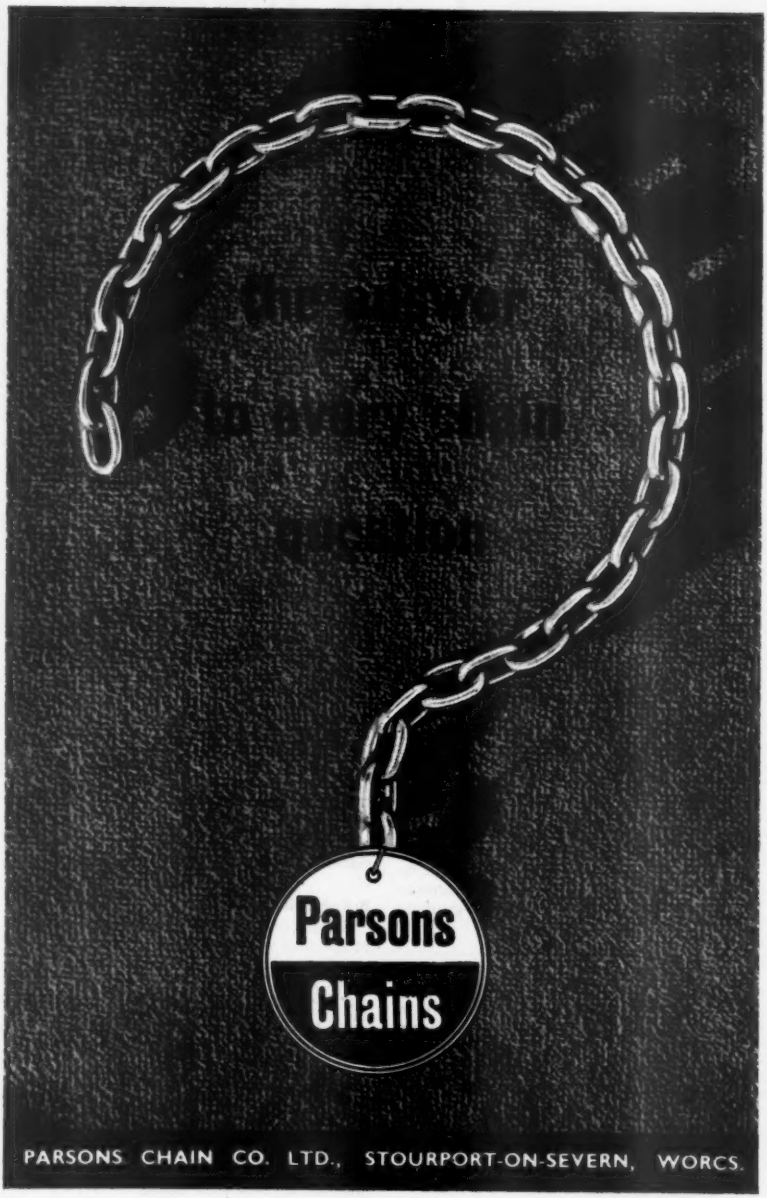
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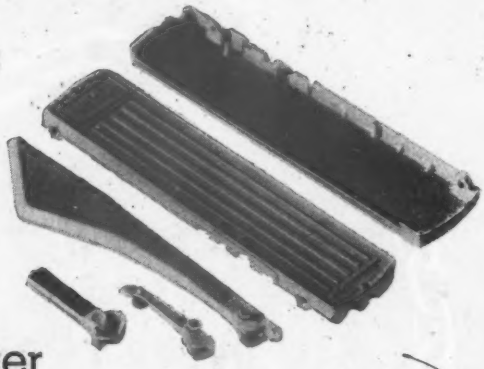

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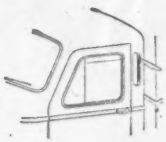

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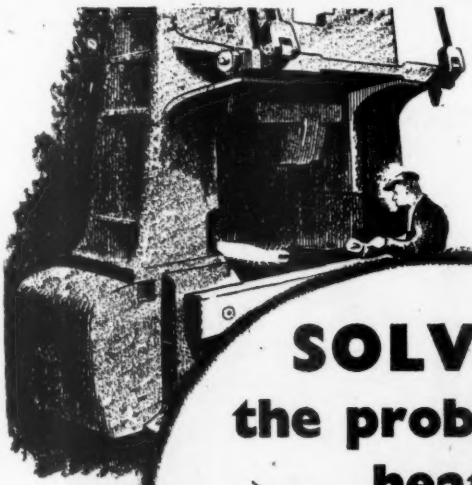

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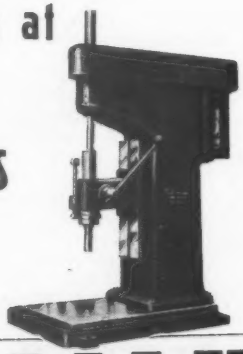

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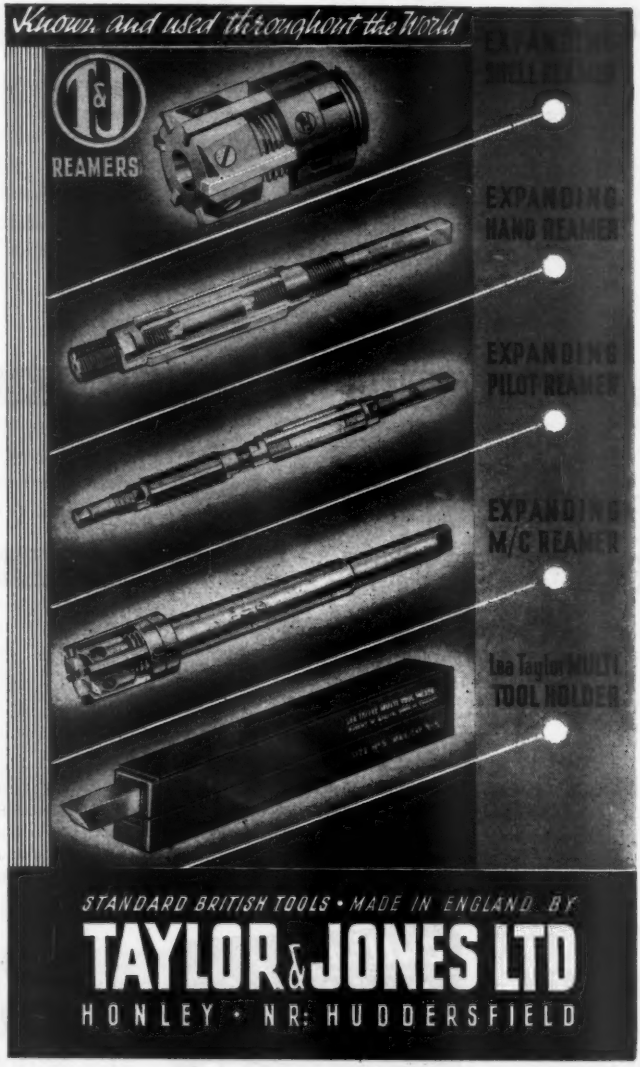
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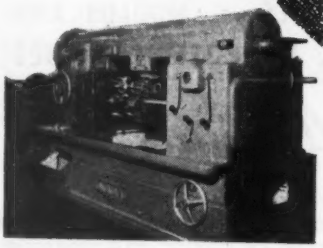

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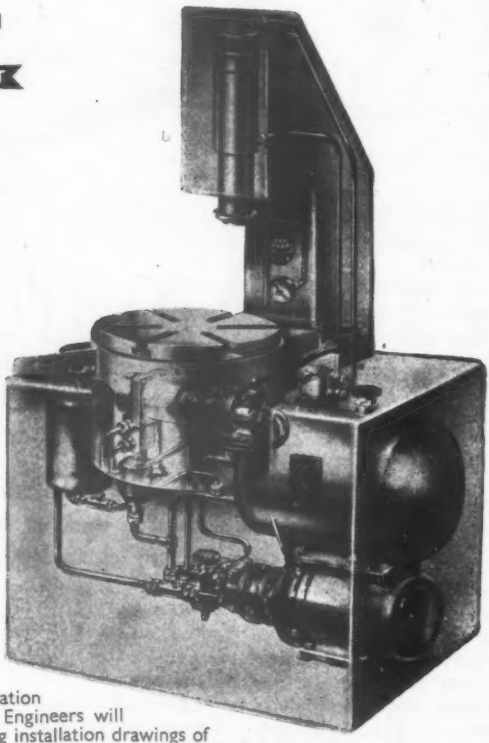

Hydraulic circuits can be designed and built up from standard Keelavite pumps motors, valves etc., to solve any problem of power distribution particularly when varying speed, varying load, frequent reversal or movements in sequence are important factors. Given detailed information relating to the proposed application of hydraulic power, Keelavite Engineers will put forward proposals, including installation drawings of the units concerned, hydraulic circuit, and any necessary electric control unit.

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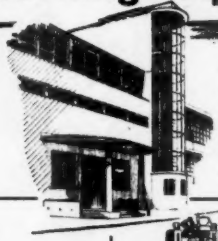

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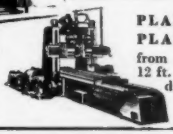

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from 6 ft. x 30 in. x 30 in. to 12 ft. x 54 in. x 54 in. bed dimensions.

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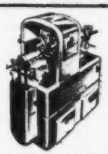
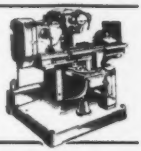
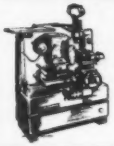


CHATWOOD AUTOMATIC HOB GRINDERS

Duel spindles permitting use of pencil wheel available to order. Capacity: with disc wheel 10"; with pencil wheel 6".





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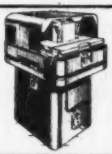

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2 double-sided wheels. Micrometer controlled feed.

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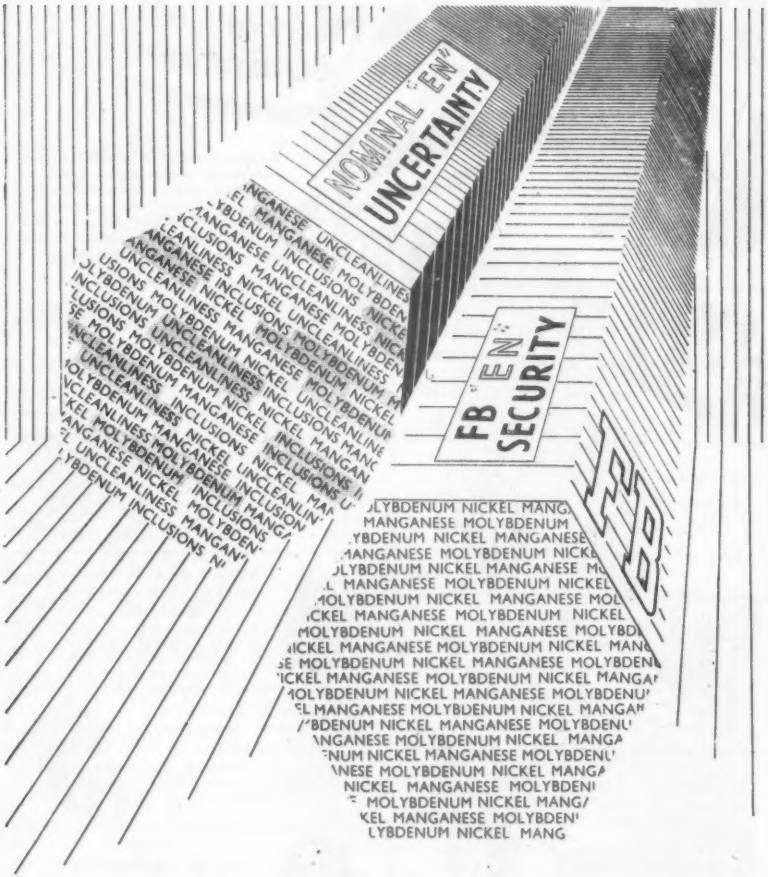

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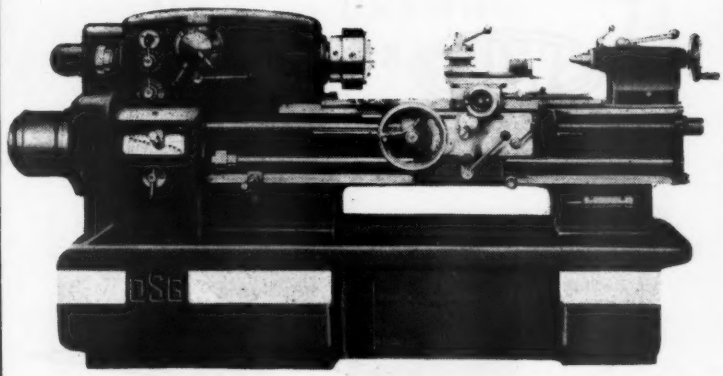

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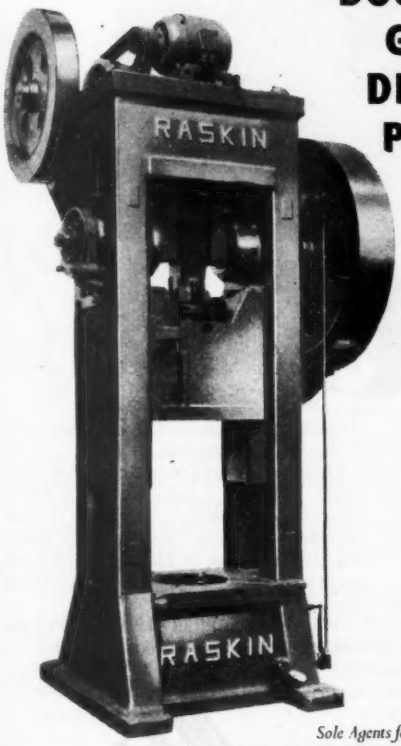

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IF ONLY a manufacturer—instead of wrestling with each separate detail of an intricate metal component—could put a full-nelson on the whole problem: could produce the complete component in a single quick operation! That's what MAZAK Alloy has made possible.

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CRANK PIN GRINDER

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and especially those who are expected to boost output on semi-obsolete machines.

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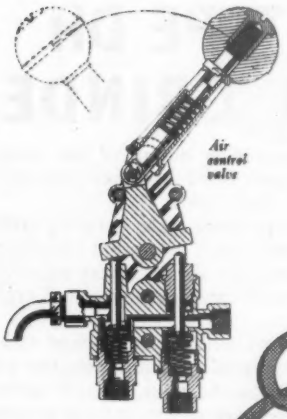

Now, don't say "my work's different!" You can't really say till you've had a talk with us. And please don't put the matter aside. If you don't need air clamp equipment we shall soon tell you. If you do need it — you need it *now*. Let's get together on this.

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Will Might, the Mill-wright
——and the PROF.
Set-too, No. TWO

"WILL MIGHT, after your disgraceful behaviour in class last session, I've a mind to give you a Hendry, meaning a good belting. But bearing in mind the fact that you are a big boy now, rather bigger than I am myself, I propose to overlook your delinquency. How well I remember in my own early days the important part belting played as a prime mover. My father, bless him, fortunately knew nothing at that time of the efficiency of Hendrys' Belts, (made up to one inch in thickness) for imparting impetus on appropriate occasions. But he did wonderful work with a strap, and even with a slipper! Today there's nothing to equal a Hendrys' Belt for every kind of drive. Strangely enough, Hendrys' make belts of any length endless. Before we meet again, perhaps you will work out how long is an endless belt, and how and where does it begin and end. That they are endless is abundantly substantiated. Under correct conditions, their efficient utility truly appears to be unending. I have reports of heavy-duty drives in use for over twenty years, and still as good as new."

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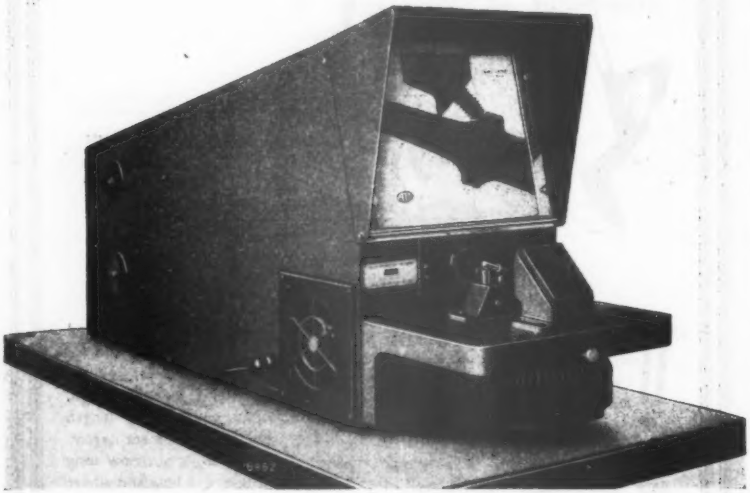

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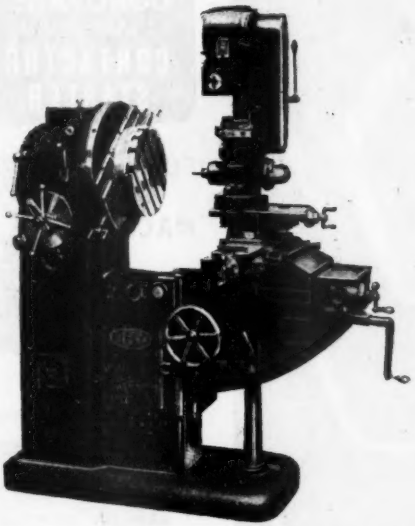

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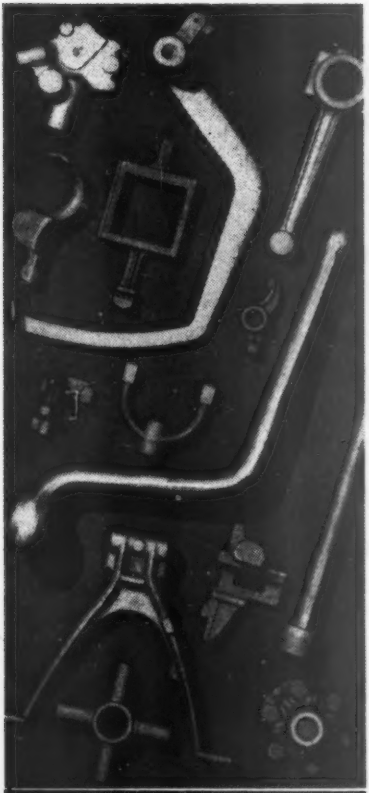

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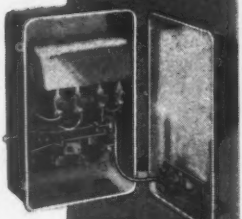

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RESISTANCE : 0.1 ohm to 5 megohms. (with internal battery).

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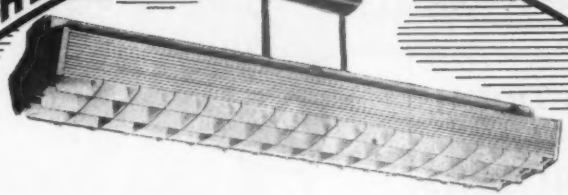

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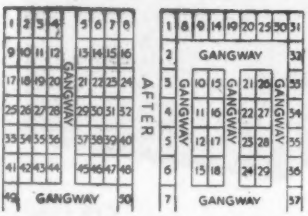

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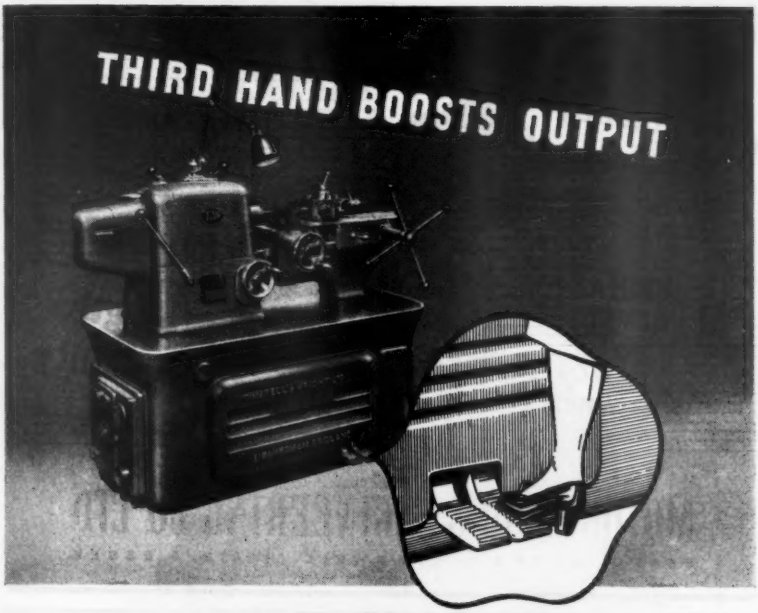

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Output positively grows.

FIVE SIZES, with bar capacities (collets) ⅜" to 2" dia. Air and/or hand locking for collets and/or chucks; various speed ranges 12 or 6 speeds per range. 100% reliable automatic bar feed. Many optional attachments. Our publications give the facts . . . . please ask for them.

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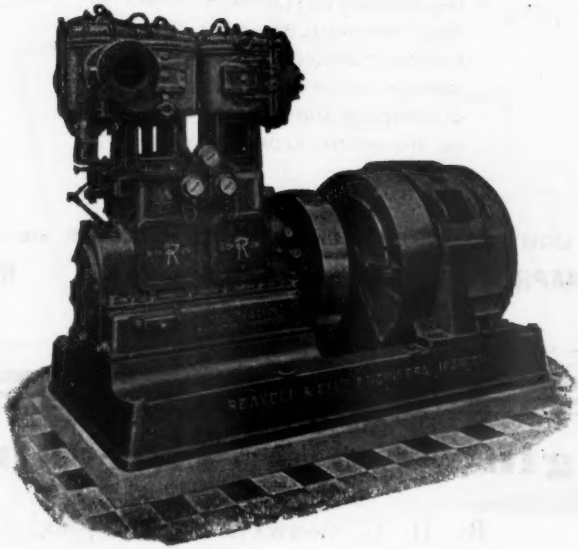

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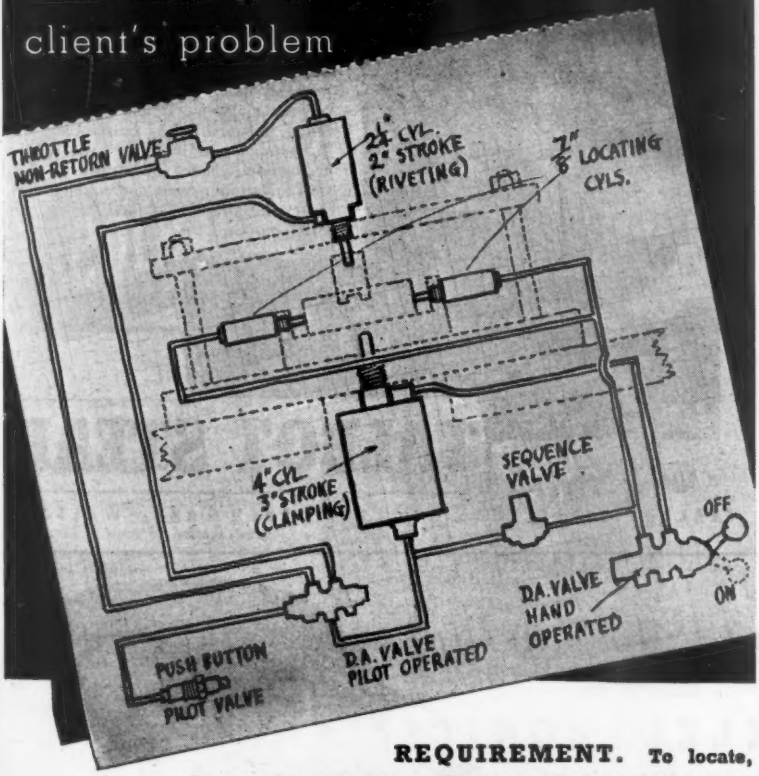

REQUIREMENT. **To locate, clamp and rivet in fixture. Riveting cylinder to be inoperative if component is not clamped and operator's right hand not on valve. Operator's left hand to control riveting operation — thereby engaging both hands as a safety measure.**

FUNCTION. **Hand-operated valve controls locating and clamping with sequence. Push-button pilot-valve operates pilot-controlled valve and riveting cylinder.**

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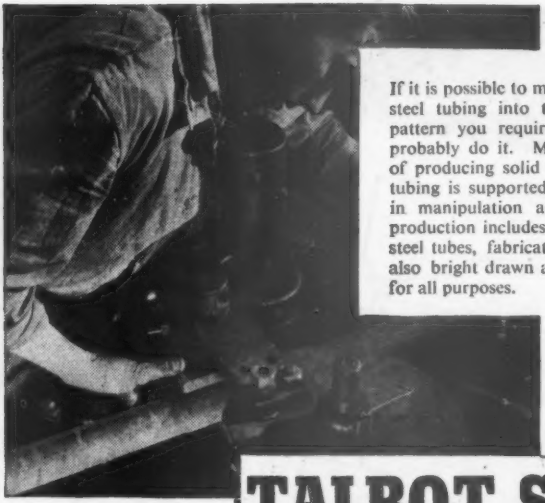

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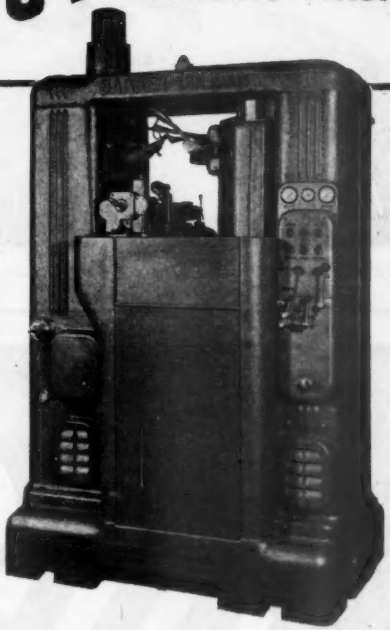

This machine, which has a capacity of 8″ diameter by 10″ long and an outstandingly rugged construction, is designed for high speed production of spur or helical gears or splines. Rigid arch-type casting, extra long vertical ways, which align the work slide, heavy short-coupled drive shafts and broad faced helical and bevel gearing, provide smooth powerful operation and minimum distortion of machine members even under the heaviest cuts. This extra-heavy structure plus accurate mounting of the hob on the taper hob spindle, ensures consistent accuracy while the machine maintains a high output, even through day-in day-out operation. Effortless control is provided by the handy centralised panel, from which a lever sets in motion the machine's semi-automatic cycle. A simple selector regulates the 8—10 to either climb or conventional cutting. Increases in hob life ranging up to 50% are achieved by fitting the new Barber-Colman 8—10 Hob Shifter.

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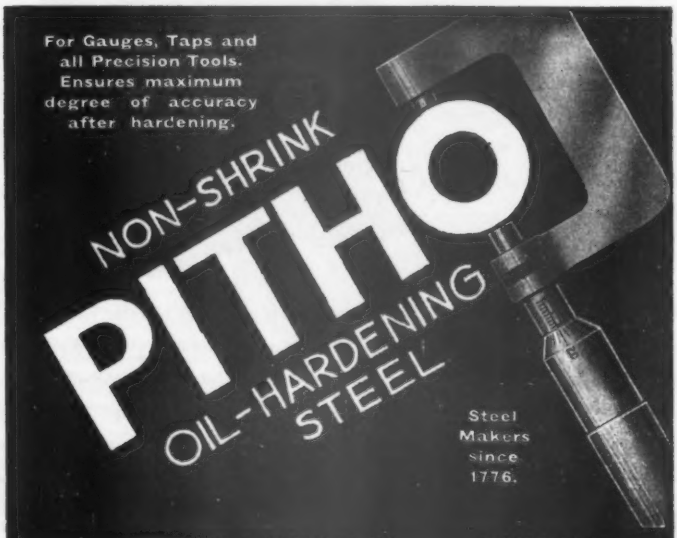
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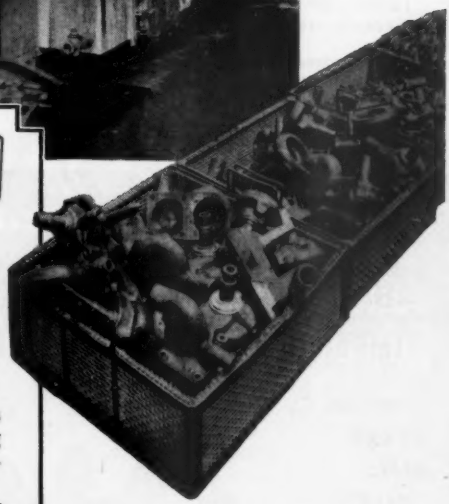

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INDUSTRIAL CLEANING MACHINES

This illustration shows a machine cleaning crank cases in the production line.

It is equally capable of cleaning small parts in baskets.

Photographs by courtesy of "Machinery."

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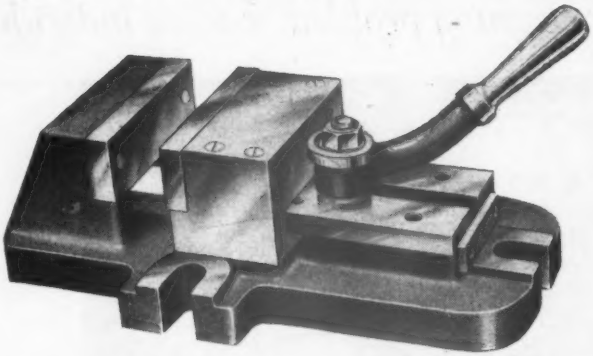

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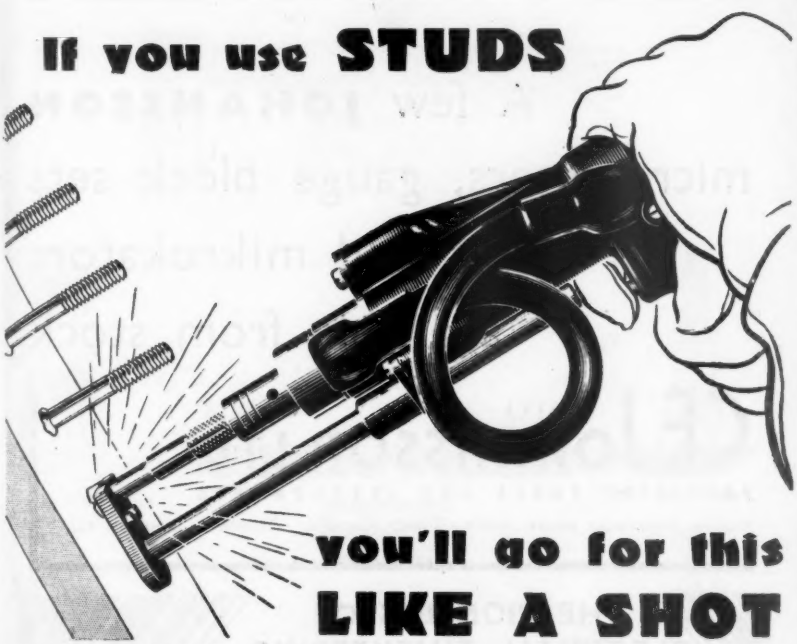

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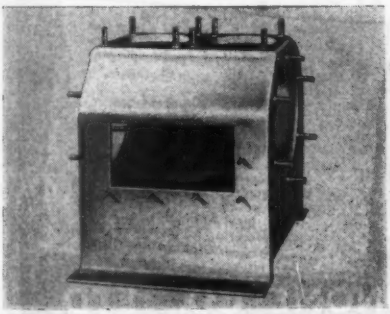

This all-welded crankcase with Nelson welded studs was designed from the start for production with Nelson gun. There is no distortion or weakening of the parent metal when Nelson studs are used.

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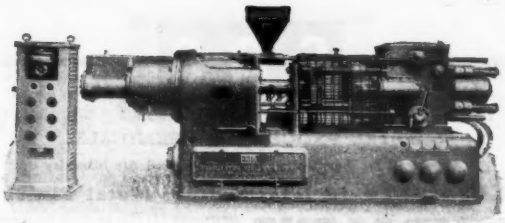

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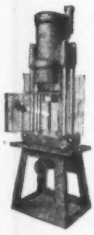

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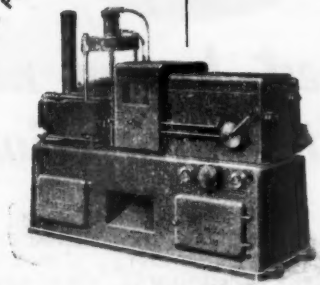

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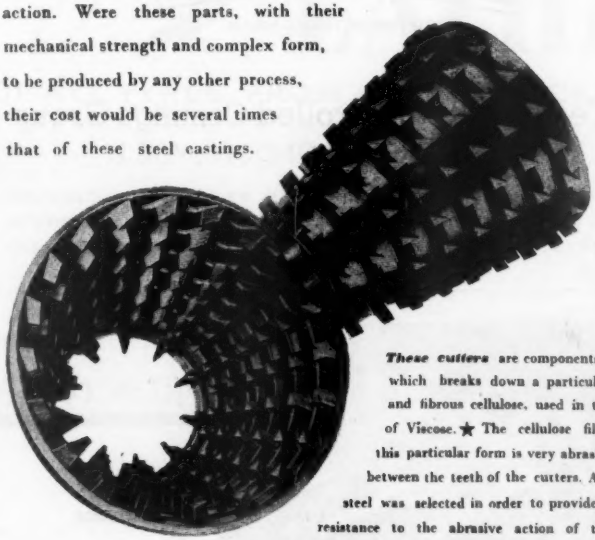

These cutters **are components of a machine which breaks down a particularly glutinous and fibrous cellulose, used in the production of Viscose.★ The cellulose fibre, which in this particular form is very abrasive, is ground between the teeth of the cutters. A high carbon steel was selected in order to provide the necessary resistance to the abrasive action of the fibre, and by suitable heat treatment, a mechanical strength of 55 tons per square inch was imparted to each casting.**

★ *Viscose is the solution used in connection with Viscose rayon spinning.*

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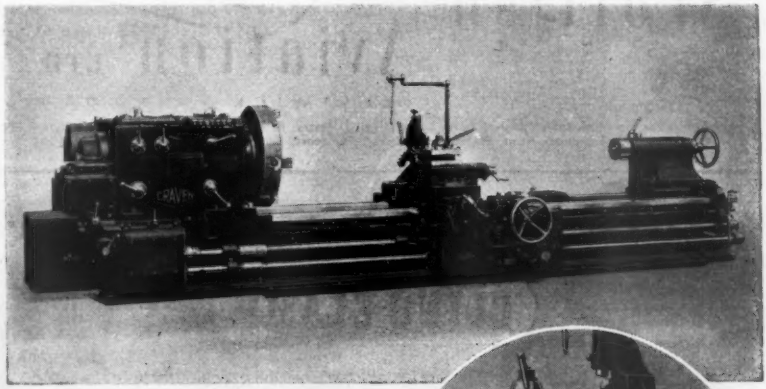

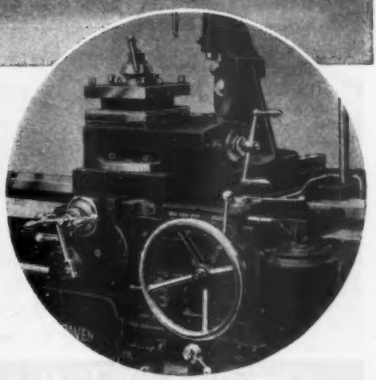

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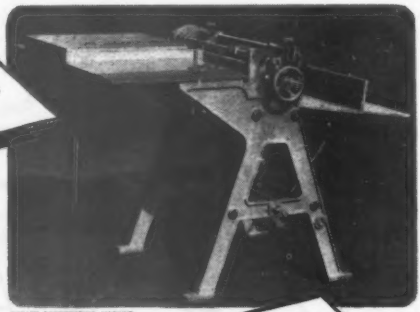

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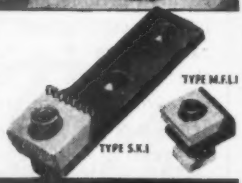

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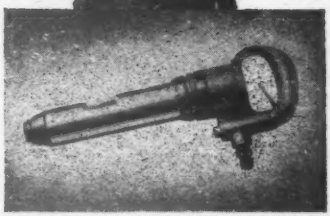
"Give me a Holman Rotogrind every time"

No matter what the job—whether it's grinding, fettling, cleaning, smoothing welds, die dressing or loco rod grinding—you can depend on a Holman Rotogrind to earn its keep. Every tool in the range is powered by a smooth-running vane-type air motor and requires very little attention beyond weekly lubrication. Like all Holman Pneumatic Tools the Rotogrind Series are easy to handle and economical in use. Full particulars of performance and applications available on request.

Size 2 Rotogrind—suitable for internal grinding, cleaning castings, etc. The range also includes precision grinding and heavy-duty types. "Straight" and "grip" handles available.

H.25

Pneumatic Hammer for chipping and caulking. Construction and action similar to riveters, and similar range in handles. Weight from 7¼ lbs. to 13¼ lbs.



Riveter. Weight from 12¾ lbs. to 19¼ lbs. Available with open or closed handle, inside or outside trigger, and usual snaps.

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